

# **Strategic Planning and Integration of NASA Earth Science Technology Program**

by

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**To My Dear Wife, Abby,  
And Our Wonderful Daughters,  
Erica, Allison, and Anna**

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## **List of Acronyms**

ACT:	Advanced Component Technology Project
AGU:	American Geophysical Union
AIST:	Advanced Information System Technology Project
AO:	Announcement of Opportunities
AST:	Aerospace Technology Enterprise
BAPR:	Broadly Announced, Peer Reviewed
BPR:	Biological and Physical Research Enterprise
CNA:	Capability Needs Assessment
CT:	Computing Technology Project
DSM:	Design Structure Matrix
EC:	Enterprise Coordination
EO:	NMP Earth Observing mission
EOS:	Earth Observing System
ESE:	Earth Science Enterprise
ESTC:	Earth Science Technology Conference
ESTO:	Earth Science Technology Office
ESTP:	Earth Science Technology Program
FBC:	Faster, Better, Cheaper
FY:	Fiscal Year
HEDS:	Human Exploration and Development of Space Enterprise
HRM:	Human Resources Management
IDP:	Individual Development Plan
IGARSS:	International Geoscience and Remote Sensing Symposium
IIP:	Instrument Incubator Project
IE:	Infusion Enabling
IF:	Infusion Facilitation
IP:	Infusion Planning
JPL:	Jet Propulsion Laboratory
KM:	Knowledge Management
NIAC:	NASA Institute for Advanced Concepts
NIAT:	NASA Integrated Action Team
NMP:	New Millennium Program
NRA:	NASA Research Announcement
OP:	Outreach and Partnership (OP)
PI:	Principle Investigator
PRT:	Pioneering and Revolutionary Technology Program
PT:	Platform Technology
RTOP:	Research Technology Operating Plan
SAS:	Systems and Architecture Studies
SBIR:	Small Business Innovation Research Program
SDM:	System Design and Management Program of MIT
SSE:	Space Science Enterprise
TAP:	Technology Assessment and Projection
TDM:	Technology Development Management

TDM1 Technology Development Management (function 1) -- Portfolio and Investment Planning

TDM2 Technology Development Management (function 2) -- Selecting, implementing, and managing low-TRL technology projects

TDM3 Technology Development Management (function 3) -- Selecting, implementing, and managing mid-TRL technology projects

TDM4 Technology Development Management (function 4) -- Selecting, implementing, and managing high-TRL technology projects

TDM5 Technology Development Management (function 5) -- Reporting and information dissemination

TIROS: Television Infra-Red Observation Satellite

THREADS: Technology for Human and Robotic Exploration And Development of Space

TRL: Technology Readiness Level

TST: Technology Strategy Team

USGCRP: U.S. Global Change Research Program

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# **Strategic Planning and Integration of NASA Earth Science Technology Program**

**J.C. Duh**

## **Abstract**

This thesis studies the strategic issues involved in the management of the NASA Earth Science Technology Program (ESTP) that is funded and managed by the NASA Earth Science Enterprise (ESE). The ESTP has major responsibilities for planning and managing technology developments for the ESE with a goal to continuously deliver and adopt advanced technologies to enable and enhance mission success for ESE, and to do so efficiently and effectively.

A system architecture framework is adopted in this thesis to analyze the strategic issues, and to devise and articulate a management system that will facilitate the efficient and effective management of the ESTP. The analysis begins with a comprehensive review of the upstream influences on the ESTP, including a review of the mission and unique capabilities of the ESE, the strategic technology needs of ESE, and the needs and expectations of ESE and other major stakeholders for the ESTP. Seven management goals of the ESTP are then derived from the synopses of these upstream influences, and are crosschecked with the list of needs and expectations for the ESTP to make sure these goals are essential to the success of the ESTP.

A total of twenty-six key management functions necessary to accomplish the ESTP goals are devised and discussed in depth. A Design Structure Matrix (DSM) is used to study the organization and coordination of these ESTP management functions based on the information flow between them. Results of this study have suggested a more effective grouping of these functions into six groups; i.e., a program planning group, three technology development management groups, a technology infusion group, and an ESTP Administration group. Necessary linkages within and across these functional groups are also devised and discussed in order to seek more effective integration, both vertically within the technology product lines and horizontally across the ESTP.

This study also discusses the critical roles of implementation process in deploying the management functions. The program-planning processes are reviewed and examined in details to serve as examples, along with some operational concepts and the associated ESTP documents affected by these processes.

Together, this thesis exemplifies an end-to-end architecture for managing the ESTP that focuses on the concept of “goal-driven”. The articulation of the Enterprise strength and stakeholders’ needs ensures that these system-driving goals are properly defined. The findings of this study include a sharpening of the definition of key management functions, a more effective functional allocation and organization, a systematic program integration that will enhance the planning, development, and infusion of advanced technologies, and the

processes that implement the program planning functions. Successful deployment of these processes implements the key management functions that accomplish the management goals. With the goals being accomplished, the stakeholders' needs are satisfied and the ESE's missions and strategies are fulfilled.

Although this study focuses on the technology program of one NASA Enterprise, it articulates issues and strategies that are common to technology programs across NASA, and therefore can be modeled and applied to other NASA technology programs. More importantly, this study intends to exemplify a system approach and thinking in pursuing management effectiveness, and that approach should be more universal in nature than the details of the recommendations herein.

## **Chapter 1 Introduction**

Strategic planning and management of technology development is a major and challenging task for any corporate with significant technical content. It involves complex interactions between product competition, patterns of technological and market change, and the structure and development of internal firm capabilities, and it requires constant decisions on which technologies to invest in, how to structure these investments, how to organize and manage innovations, and how to anticipate and respond to the behaviors of competitors, suppliers, and customers. NASA, being a cutting edge science and technology agency, faces most of these challenges and more in its planning and management of technology programs.

This chapter provides an overview of the history and role of advanced technology within NASA. Underlying principles that guide technology planning and implementation, and some of the issues influencing the process are described. This overview illuminates the motivation and objectives of this study, which is discussed in this chapter along with the research approach and the outline of this thesis.

### **1.1 NASA and Advanced Technologies**

The creation of NASA in 1958 had its root in the perceived lag of US technological capabilities behind the Soviet Union triggered by the Soviets' launch of Sputnik 1 in October 1957 [1]. The National Aeronautics and Space Act of 1958, upon which NASA was created, specifically charged NASA with, among others, the following purpose of its activities: [2]

“Preservation of the role of the United States as a leader in aeronautical and space science and technology”

Over the past 43 years, NASA has accumulated a rich history of unique technological and scientific achievements, and has become the premier leader in technologies for Earth observing, space exploration, astronomy, and aeronautics. NASA's technology research and development has not only enabled a series of high profile missions from Moon landing to Mars Pathfinder, from X-15 to Space Shuttle, and from Hubble Space Telescope to the Earth Observing System, it has also resulted in numerous "spin-offs" in wide-ranging technical and

commercial fields that has rewarded the US economy and society with new businesses and markets, quality jobs, and improved quality of life.

NASA's challenges, however, encompass more than science and technology. Constant downsizing and budget squeezes had challenged the Agency throughout the 90s, an era when NASA saw its budget decline in constant dollar terms by 21% and its workforce lowered by 25%. Yet during the same time, NASA had responded smartly to the "Faster, Better, Cheaper" (FBC) philosophy with technology innovations that resulted in a 4-fold increase of the average number of missions launched per year, a 40% reduction in time, and a 67% reduction in cost to develop Earth- and space-science spacecrafts. Greater than 97% of NASA's budgetary investment in flight missions resulted in successful outcomes [3]. Unfortunately, the few failures, such as the Mars Climate Orbiter and the Mars Polar Lander, had led many observers to believe that the FBC approach might have pushed too far.

Consequently, four independent panels were chartered to investigate the two Mars Program failures and the Shuttle wiring problems, and to conduct a generic assessment of NASA's approach to executing the "Faster, Better, Cheaper" (FBC) projects. A NASA Integrated Action Team (NIAT) was subsequently formed to assess and respond to findings and recommendations contained in the four reports released by these independent panels [4, 5, 6, 7], and to define an integrated plan to address opportunities for improvement from an Agency perspective. The detailed action plan is documented in a NIAT report released in December 2000 [3].

A common argument against the philosophy of FBC is that cost, schedule, and performance form the three-dimensional trade space for project management trade-offs; constraints can only be placed on two out of the three goals in "FBC", the trade-off in the third goal will reflect in poor results. However, history can show that civilizations continuously move in a direction characterized by FBC, with the help of the technology advancement. Therefore, the true trade space for project management should possess one more dimension, that of technology advancement. Along this view, the FBC Task Panel observed that managing

technology advancement is extremely important, especially with low-cost missions that typically require shorter development time.

The FBC Panel also pointed out that “NASA’s technology planning was weak” and “needed to be fixed” in order to fully exploit advanced technology to enable and enhance new and challenging science programs/projects consistent with short development cycles. The other three investigation panels shared similar concerns about the quality and effort of NASA’s technology planning and management. Consequently, the NIAT team identified and reflected the importance of “Delivering Advanced Technology” as one of the five key themes in the NIAT deliberations and in its final report.

The NIAT report further laid out three codependent elements for NASA to successfully plan, manage, and deliver advanced technologies:

1. A balanced investment strategy to maintain a technology pipeline that meets the near-, mid-, and long-term mission needs,
2. A well-defined technology planning process that facilitates the identification of opportunities and ensures the efficient transition of new technologies into missions, and,
3. A logical and thorough technology life cycle management approach that enables new levels of performance and capability and the ease of infusion into missions.

These three elements sum up well the fundamental challenges and goals of planning and managing technology programs of NASA. The importance of technology planning and management to NASA cannot be overstated because NASA relies on advanced technologies for its continued success and to maintain its eminence as the world leader in civil space and aeronautics, especially in an era of continuing budget pressure and diminishing resources.

## **1.2 Technology Planning and Management at NASA**

There are two different organizational forms to manage technology R&D, a centralized corporate R&D unit vs. a decentralized R&D organization. The former generally yields better functional output and exploits the creativity synergy, but it runs the risk of becoming

an “ivory tower”. The decentralized R&D organization is usually more product-oriented and is more closely linked to the needs of the business. However, this decentralized organization may become “captured” by the business, and fail to prepare the corporation for the longer term. Henderson [8] observed an oscillation between these two organizational forms in some of the largest US industrial companies, and attributed it to the intention to correct the shortcomings of one form if it were to go too far to the extreme. It is therefore an important balancing act for corporate executives to build a world class R&D capability and, at the same time, closely link it to leading edge product development.

NASA implements its Mission through five Strategic Enterprises:

- the Aerospace Technology Enterprise (AST),
- the Biological and Physical Research Enterprise (BPR),
- the Earth Science Enterprise (ESE),
- the Human Exploration and Development of Space Enterprise (HEDS), and
- the Space Science Enterprise (SSE).

Analogous to the business units of a corporation, these five Enterprises hold program formulation and funding responsibilities for the majority of NASA’s business.

To balance the need to be responsive to the Enterprises with the need to provide the Agency longer-term technological capabilities, NASA has structured its technology programs into a set of “Enterprise sponsored” (decentralized) technology programs and a few “cross-Enterprise” (centralized) advanced concept and technology programs. According to the NASA Technology Inventory [9], the five Enterprises held the funding responsibilities for the majority of NASA’s technology development activities that accounted for about 84% of the total NASA investment of \$1.5 billions in technology R&D in FY2001. The remaining 16% was investment in “cross-Enterprise” programs such as the Pioneering and Revolutionary Technology Program (PRT), the Small Business Innovation Research Program (SBIR), and the NASA Institute for Advanced Concepts (NIAC).

It is the responsibilities of each Enterprise to ensure that its sponsored technology programs are closely aligned with its mission goals and Enterprise needs, and that mechanisms are

provided to transfer successful maturing technologies into its missions in a timely fashion. However, just like the decentralized R&D approach discussed earlier, there is a natural tendency for these Enterprise technology programs to focus more on near-term technology needs and less on advanced technologies that mature further into the future. The obvious reason is that the pay-off from investing in far-term, advanced technology concepts is uncertain and, even if successful, could be many years in the future. On the other hand, the near-term Enterprise needs always have higher visibility because the upcoming science missions tend to “pull” the needed technologies into maturity and can reward mission managers more immediately. It is therefore a crucial task for Enterprise executives to ensure the Enterprise’s technology programs reflect balanced near- and far-term goals by recognizing the need to adequately support the far-term, advanced concepts; concepts that ensure a healthy technology pipeline for the future.

To balance these “science pull” technology programs with far-term programs that “push”; i.e., enable, future missions, the NASA Chief Technologist has championed advanced concept and technology programs at the Agency level that ensure NASA, as a whole, supports those advanced technologies with potential to revolutionize how NASA does business in the future [10]. The challenge to these “technology push” programs is to avoid the “ivory tower” syndrome while maintaining a far-term revolutionary vision. To establish a critical linkage with the Enterprises, this revolutionary vision would be best developed if jointly with the Enterprises’ advanced planning teams such as the Earth Science Vision Team and the Decadal Planning Team to benefit from the broadest participation of forward thinkers, and to capitalize on the synergism among various Enterprises. This joint vision also facilitates the Enterprises’ buy-in to the advanced technology concepts developed by these cross-Enterprise programs and help link these programs to the Agency’s future missions.

### **1.3 Motivation and Objective of the Study**

Recognizing the challenges of managing NASA’s technology programs, and the fact that Enterprises have the major responsibilities for the Agency’s technology planning and development, this thesis chooses to study the Earth Science Technology Program (ESTP) that is funded and managed by the NASA Earth Science Enterprise (ESE).



The objective of this study is to provide a framework under which a comprehensive planning of an Enterprise-focused technology program can be conducted. Critical program management functions are defined following a set of management goals that are synopsized from a comprehensive study of the needs and expectations of the Enterprise and other major stakeholders. Coordination and integration of these functions for efficiency and effectiveness are examined. Through the deliberations in this thesis, the three critical elements for NASA to successfully plan, manage, and deliver advanced technologies as identified by the NIAT report [3] and discussed in section 1.1 will be addressed. The subtle, yet critical, balance between the science-pull and the technology-push development efforts, in the context of an Enterprise-focused technology program, will also be articulated. Therefore, although this study focuses on the technology program of one Enterprise, it attempts to address issues and strategies that are common to technology programs across the Agency, and therefore can be modeled and applied to other NASA technology programs.

#### **1.4 Approaches and Content of the Thesis**

The framework used in the analysis and the deliberation of this thesis follows a modified system architecture framework of Edward Crawley [11] that is depicted in Figure 1.

The analysis begins in Chapter 2 with a comprehensive review of the upstream influences on the ESTP that include the heritage, mission, Enterprise strategy, and business processes of the ESE. The needs and expectations for the ESTP from the ESE strategic perspective are then enumerated. The needs and expectations of other major stakeholders for the ESTP are also deliberated. These upstream influences then drive and define the strategic and management goals of the ESTP. In Chapter 3, critical management functions necessary to accomplish these ESTP goals are defined and designed. These functions are also crosschecked against the ESTP management goals to make sure the set of functions are sufficient to accomplish these goals. The information flow and the coordination among these management functions are examined in Chapter 4 using the Design Structure Matrix (DSM) method [12,13]. The DSM method, popular for industrial product design and project planning and management, provides a basis to discuss the organization and integration of

ESTP. The establishment of management processes to implement these functions is also discussed in Chapter 4 with extended examples given for the planning functions. Finally, Chapter 5 concludes this thesis with a brief summary.

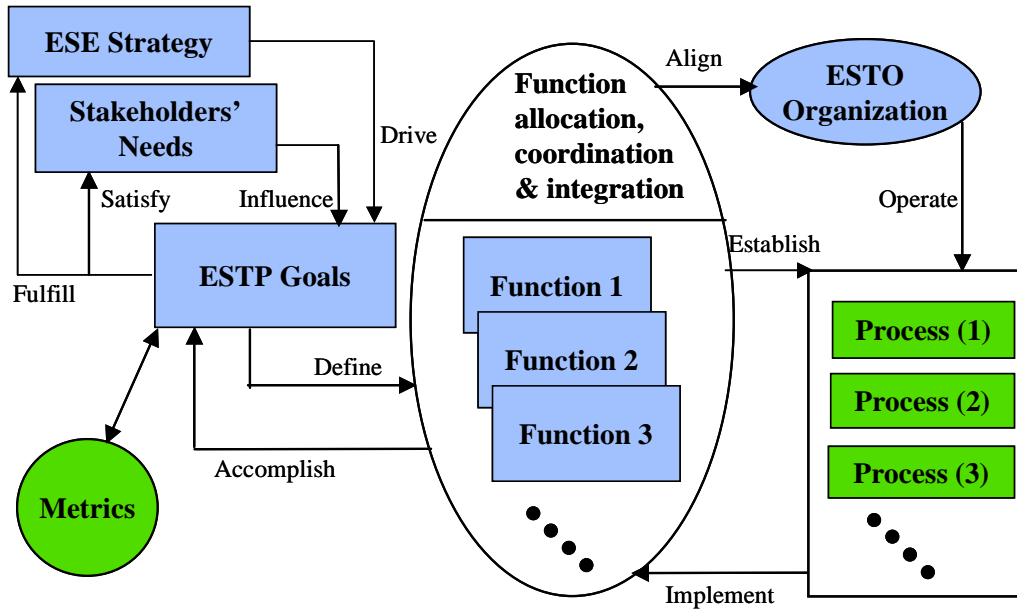


Figure 1: A System Architecture Approach

Fifteen experts were interviewed for this study that included senior program and project managers of NASA and other Federal Labs, ESE Advisory Committee members, and practicing scientists and technologists. These interviews generated the majority of the raw data that were synthesized and synopsized in this thesis. While these interviews provided great insight into the issues and strategies of the subject study, the responsibility for the findings and conclusions of this thesis rests entirely with the author. For reference purpose, a sample list of questions used to guide interviews with NASA program managers is included in Appendix A.

It should be noted that the ESTP is an existing ESE program, this study has therefore drawn extensively from existing ESTP documents and its managing practices. The documents referenced include the Earth Science Technology Program Plan [14], the ESE Technology Strategy [15], the Earth Science Technology Office (ESTO) Integrated Technology

Development Plan [16], and the ESE Technology Infusion Plan [17]. Wherever appropriate, this study compares its findings against the current ESTP documents and practices with due criticism and suggestions.

## **Chapter 2 The Needs and the Goals for the ESTP**

Among the many concepts and practices of corporate, business, and function strategic planning, it is commonly agreed that the functional strategy such as a technology strategy must be tied to and guided by the corporate and business strategies. Hax and Majluf [18] articulated that corporate and business strategies provide the most important inputs for a technology development strategy because they define the basic requirements a technology program has to attend, and the critical role the technology program plays in developing the core competencies for sustainable competitive advantages. The importance of an effective linkage between technology and business strategies is further demonstrated in an extensive survey conducted by Roberts [19]. The survey showed that the management linkage at the executive level between technology and business is vital to a company's strategic management of technology efforts and to its business performance.

To establish the strategic linkage between the ESTP and the ESE and to lay the foundation for the ESTP program planning and integration, this chapter looks into the mission of the ESE, the unique capabilities that the ESE offers to its stakeholders, and the needs for an Enterprise-focused technology program like the ESTP. The needs and expectations of other major customers and stakeholders of the ESTP are also reviewed.

### **2.1 The NASA Earth Science Enterprise (ESE)**

**The Heritage and the Evolution:** NASA's contributions to global observations of the Earth from orbiting satellites began early in the Agency's history. In its first 10-year plan presented to Congress, NASA called for an expanding program that included, among others, the weather satellites to improve our knowledge of Earth's broad weather patterns. The development and launch of the Television Infra-Red Observation Satellite (TIROS-I) in 1960 marked the first weather observation satellite that took pictures of Earth's cloud covers and major land features on a global scale from an orbit 450 miles above the Earth. Eight years later, the first color picture of the entire Earth taken by the Apollo astronauts on their way to the Moon further promoted an international awareness of the Earth as a stand-alone system in

the vast void of space, and the appreciation of the fragility of its environment and the lives within.

The visual confirmation of the “Antarctic ozone hole” by remote sensing data obtained from space between 1979 and 1984 was NASA’s contribution in underscoring the impact of human activities on planet Earth and the inter-connectivity of the global environment. These scientific discoveries led to the 1987 signing of the Montreal Protocol by 148 nations and set the precedent that consensus and quality science can, and should, come before political influences in policy making.

The “Antarctic ozone hole” and other global warming signs heightened the public concerns over global environmental change that underpinned the launch of the U.S. Global Change Research Program (USGCRP) in 1989, a multi-agency undertaking of which the NASA contribution became the NASA Earth Science Enterprise (ESE).

To further scientific understanding of global change, ESE has embraced the concept of “Earth System Science”. This concept emphasizes the Earth can only be understood as an interactive and integrative system that includes the atmosphere, oceans, land, and life. ESE has, therefore, placed a strong focus on interdisciplinary science to better understand the interactions between Earth system components so that credible and policy-relevant science conclusions can be drawn. The launch of the first series of Earth Observing System (EOS) satellites, beginning in 1997, opened a new era for long-term monitoring of a set of key parameters of air, land, water, and biosphere necessary to identify meaningful trends of global change and to separate human effects from the natural variability. NASA has thus entered another chapter in its history of accomplishments in understanding the Mother Earth and contributing to the human sustainability on the blue planet. A chapter that began with a weather satellite program 42 years ago and evolved to a suite of systematic and exploratory remote-sensing satellites, and from a discipline-specialized study to a system perspective and interdisciplinary approach.

**ESE Mission:** The mission of ESE, as stated in the ESE Strategic Plan [20] and evident from its heritage and evolution, is to:

**“Develop a scientific understanding of the Earth system and its response to natural and human-induced changes to enable improved prediction of climate, weather, and natural hazards for present and future generations.”**

**ESE Business Process:** The processes that ESE engages to accomplish its mission are briefly summarized in Figure 2.

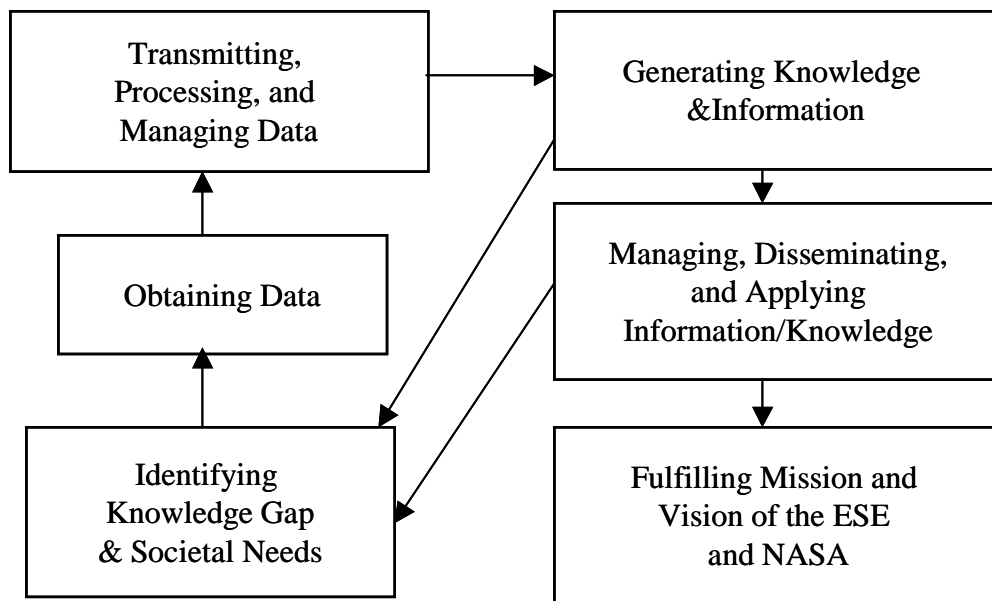


Figure 2. ESE Business Processes

Guided by science and societal needs, the ESE advances its knowledge and technology capabilities to understand and predict environmental changes through iterative and interactive improvements in observation and scientific processing, modeling, and understanding. The word “business” is chosen deliberately because the Earth Science Enterprise is in a “business” mode of operation, as the word “Enterprise” implies. It acquires and disseminates valuable knowledge and information that will improve our life here on Earth and protect our planet for future generations. As in any business, only when the ESE-produced information

and knowledge products are widely disseminated to and accepted by the user community, and the benefit from the ESE investment is effectively articulated to our ultimate stakeholders – the American taxpayers – can the business prospects and the costs of the ESE be justified and sustained.

Strategically, the ESE has planned and is engaged in an extensive web of interagency and international partnerships that are listed in the ESE Strategic Plan [20] because the field of participation in the global change research is global indeed. The major issues of our environment transcend the national boundaries and require international collaboration. More importantly, as pointed out by Kennel, etc. [21], the readiness of any nation to accept science findings or recommendations regarding environment may depend on that nation's involvement in the processes of data acquisition and analysis.

**Unique Capabilities of ESE:** In this global web of global change enterprise, NASA's unique contribution is its vantage point from space. Although observation without science does not generate systematic knowledge as to the causes and consequences of global change, it is recognized that the provision of adequate observation and monitoring is a prerequisite to improving our knowledge [22]. Furthermore, space-based remote sensing is bound to contribute a large part of the needed observations because the coverage required to observe Earth system changes must be global in space and continuous in time to resolve the many dynamic, micro-scale processes on a global scale; a requirement only remote sensing can conveniently meet. As a research and technology Agency, NASA's unique competency is the combination of space-based observations, research, and modeling that provides new tools and knowledge to enable improved assessment and prediction of global change and its impacts to the environment.

## **2.2 The ESE's Technology Needs and Its Needs for the ESTP**

**ESE's Technology Needs:** Even though faced with continuous budget pressure, the ESE continues to adopt and advance a broad array of technologies considered essential to the effective execution of its business processes illustrated in Figure 2:

- T.1 Advanced instrument technologies, key to providing needed data for monitoring and scientific research, should be sought to lower the cost of meeting existing observation requirements and to enable new science measurements while improving accuracy and increasing spatial and temporal coverage.
- T.2 Information system technologies are becoming major challenges of the future as the volume of data from space-borne sensors continues to increase, and in some cases, by orders of magnitude. End-to-end information system technologies need to be developed that will allow the vast amount of valuable data obtained from space to be properly transmitted, timely processed, and widely and readily disseminated to the users communities. The advancement of the information system technologies is also critical to the continuous growth of the users' base, and the adoption of ESE information products by the users.
- T.3 Platforms are defined as host systems for sensor suites. The development of advanced platform technologies, essential for enabling the long-range Vision [30] of the ESE, will allow platforms to be lighter and smaller, consume less power and other resources, and to operate with increased flexibility using standardized platform interfaces. Intelligent and adaptive platforms, including precision formation flying, will also enable both the ESE Vision goals and new science measurements and applications.
- T.4 Computing and modeling is a powerful tool for studying a dynamic system having complex feedbacks, such as the Earth, and for making predictions about its dynamic behaviors. Although the basic physical, chemical, and biological process models are more science oriented, advances in computing technologies are needed to improve code interoperability, portability, and data assimilation, and to promote a system architecture that will allow an integrated multi-disciplinary model for global change prediction be modularly built.

**ESE's Needs for the ESTP:** The ESE Strategic Plan [20] identifies three major functions necessary to carry out the Enterprise mission: i.e., science, applications, and technology. Therefore, there is a clear strategic need for an Enterprise technology program. Specifically, the following needs for the ESTP have been identified from the ESE documents and from interviews with senior ESE managers:



**2.2.1 To identify and manage advanced technology development projects that are needed for ESE to effectively and efficiently execute its strategies and business processes (as discussed earlier in this section).**

As discussed in section 1.2, it is the basic requirements of an Enterprise technology program to ensure that its investment is closely aligned with the Enterprise needs and mission goals. It was also discussed earlier that the ESE would need advanced technologies in the areas of instrument, information system, platform, and computing.

**2.2.2 To balance the mission-specific short-term technology solutions with a consolidated advanced technology program that allows the investment priorities be based on Enterprise priorities rather than on local optimization at project level, thus achieving overall cost-effectiveness of technology investment.**

In the past, much of the technology development of NASA was carried out within the framework of individual projects. The emphasis was necessarily mission-specific, short-term fix, and evolutionary in nature. Since cost-benefit trades were carried out within the individual project, there was little motivation to develop “generic” capabilities for the benefit of multiple missions, especially for future mission needs, and cost-saving technologies that require significant resource commitment became unaffordable. This tended to perpetuate the use of older, less cost-effective engineering solutions and create a “technology-averse” design environment. Consolidating the Enterprise technology program outside of the projects, and linking it to the Enterprise priorities allows the program investment to be based on optimization of the global return on technology investment, thus ensuring the overall cost-effectiveness of the program.

**2.2.3 To reduce costs, schedule uncertainties, and risks of performance by developing and maturing technologies to adequate Technology Readiness Levels (TRL) prior to implementation.**

When technologies were developed under the auspices of individual projects, the uncertainties associated with the R&D effort frequently caused cost overruns, schedule slips, or performance risks. These adverse impacts contributed to a “risk-averse”

culture in flight project management. A consolidated Enterprise technology program allows high priority technologies to be developed prior to the mission selection that occurs only when the technologies needed for the mission are matured to an adequate performance and risk level to sufficiently satisfy science needs. This process of mission formulation and selection is shown in Figure 3 [14]. By applying financial theories of option pricing to capital investment, it can be shown that such a consolidated technology program can expand mission opportunities and enhance the overall investment returns [23].

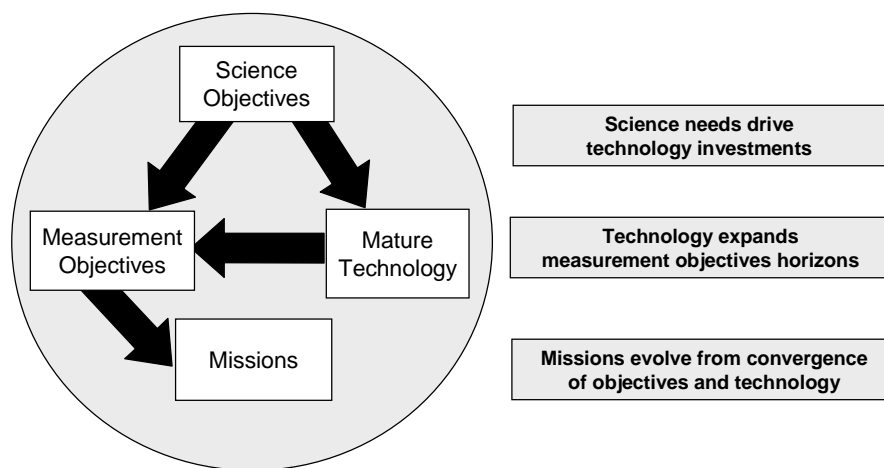


Figure 3. Science Linked with Technology Enables Missions

#### 2.2.4 To infuse the developed technologies into missions or operational systems.

Separating technology development from the projects, though beneficial as discussed in 2.2.2 and 2.2.3, does create additional barriers for infusing technology advancement into future science missions. Since the project manager did not make the decision to invest in these technologies, there may not be the ownership for the necessary “buy-in”, or the needed familiarity with the performance and cost benefits these new technologies offer to entice the risk-averse project managers to adopt these technology advances. Especially with principle investigator (PI)-led missions, PIs are typically not a resident at a NASA Center, and may be even less involved, and thus less familiar with the Enterprise technology program. The goal of the ESTP to infuse advanced, yet mature,

technologies into future missions becomes critical for the benefits of the investments to be realized.

#### **2.2.5 A need to provide a central technology management service at the Enterprise level that includes planning, coordination, integration, and outreach**

Because technology constitutes one of the three main functions that enable the ESE's mission, the ESE needs to make sure the technology function is adequately represented at the Enterprise management level in order to facilitate program/budget planning, to coordinate with science and applications functions at the Enterprise level, and to integrate the various technology development activities of the ESE into a coherent technology pipeline; a pipeline that will provide the Enterprise with innovative technologies on a continuous basis. To support leveraging of the ESE's investments, ESE needs to make sure there is a coherent coordination and collaboration with other NASA technology programs, and effective partnerships with industry and operational agencies. Both objectives would be best served with a central technology management arm at the Enterprise level.

### **2.3 Major Stakeholders' Needs and Expectations for the ESTP**

In this section, an attempt is made to identify and list the needs and expectations of the following major stakeholders of the ESTP: technologists, scientists, applicationists, NASA Centers, and other technology programs of NASA and other agencies. Industry and academia are not included as major stakeholders on an institution basis, but the categories of scientists, technologists, and applicationists should adequately represent the interests of industry and academia.

Major sources of information used for the synopses in this section came from the fifteen interviews conducted with field experts in science, technology, applications, project and program management, and technology management. However, the needs and expectations of the major stakeholders of the ESTP, summarized and discussed in this section, are the conclusions of this author.

It should be noted that the listed stakeholders in this section constitute the majority of the Earth science community that ESE serves, therefore, many of their needs are being absorbed and represented by the ESE's needs for the ESTP, and was already discussed in section 2.2. To avoid repetition, we will only discuss in this section the more distinctive needs of these stakeholders.

### **Technologists' Needs for the ESTP:**

#### **2.3.1 To articulate technology development priorities clearly so the R&D effort can be better aligned and the proposals better focused**

Clearly articulated development priorities and a committed program investment solicitation schedule will help guide the technologists' efforts a great deal.

#### **2.3.2 To elucidate the various technology development vehicles in such a way as to allow the technology to be matured to as high a Technology Readiness Level (TRL) that is needed and that is obtainable**

NASA measures the progress of technology development using a set of Technology Readiness Levels that measures the "readiness" of the technology for application and is an indication of the risk level associated with adopting this technology. The definition of the TRL is included in Appendix B.

ESTP and other NASA technology programs employ different investment vehicles to segment the development effort based on the TRL of the technologies. An example within the ESTP is the Advanced Component Technology (ACT) Project that funds technology development with TRL from 2 to 4, and the Instrument Incubator Project (IIP) that funds technology development with TRL from 4 to 6. The purpose of employing separate vehicles is to establish and enforce "decision gates" in the technology pipeline to assess the progress and potential of the technology. Such a mechanism weeds out less promising technologies and thus saves development costs that could increase significantly at the higher TRL levels. As a consequence, "orphan" technologies will result from this gate-selection process, and most are for sound technical reasons. However, because there are multiple technology programs

in the Agency, multiple pathways exist to mature a technology upward to a necessary TRL, and the ESTP, as the ESE's technology management arm, is positioned to effectively apply the Agency's many and various technology development vehicles.

### **2.3.3 To provide adequate opportunities for flight validation/qualification of high-priority technologies**

With the current design of the ESE technology programs, there is an unmet need for technologies to be matured beyond TRL 6 and to be flight validated/qualified. The opportunities to pursue such flight validation/qualification are being offered by the New Millennium Program (NMP), but the opportunities are limited and the selection criteria are not completely driven by technology needs. Although the NMP is charged with a charter to test new instruments, spacecraft systems and subsystems, and mission concepts in actual space flight environment for ESE and SSE, the NMP program goals state that it also expects its missions to return scientific data as a "byproduct" [24]. The expected science return from the NMP flight may have influenced the mission success criteria and made the program more risk-averse than a technology validation program should be, and as a result, the NMP has become more of a mission builder itself rather than a technology validation/qualification program. Since its inception in 1994, the cost and time required to build and operate a flight project has limited the NMP Earth Observing (EO) series to just one flight, the EO-1 mission, with another mission, the EO-3, currently in the formulation stage. Future opportunities for flight validation and qualification of advanced technologies appear to be as scarce. As a consequence, many technologies have to stop at TRL 6 and thus limit their opportunities for infusion into future missions. There is, therefore, a clear need for the ESTP to ingeniously create other opportunities and mechanisms for flight testing/qualification of high-priority and promising technologies so the benefits of the ESE technology investments will be carried to full fruition.

### **2.3.4 To help bridge connections with potential mission PIs**

Early involvement of the science community and continuous and broad dissemination of the technical information of the technology development projects is one important

step to solicit “buy-in” from potential mission PIs and to overcome the infusion barriers created by additional organization boundaries. ESTP should seek every possible opportunity, not to “sell” its technology projects, but to help bridge connections between its technology PIs and the science community to facilitate future technology infusion.

#### **2.3.5 To sponsor some fundamental technology R&D**

The balance between the “science pull” and the “technology push” in the context of NASA technology development programs has been rather extensively discussed in section 1.2, along with the need for the ESTP to fund some longer-term advanced concepts.

#### **2.3.6 To commit to funding stability and continuity necessary to raise the TRL to a desired level**

The need for funding stability and continuity is recognized and will be discussed together with the core competence needs of the NASA Centers later in this section.

### **Scientists’ Needs for the ESTP:**

#### **2.3.7 To invest in in-situ measurement technologies including airborne, and calibration/validation work**

Although spaceborne measurements have the distinctive advantage of global coverage, in-situ measurements do serve some important observational and data needs and, in general, are less expensive to develop than the space-based remote sensing technologies. A comprehensive observational system must include both remote sensing from space and in-situ measurements. When an in-situ measurement concept can be explicitly tied to a high-priority observational need, ESTP ought to take advantage of the opportunity and maximize the investment returns.

#### **2.3.8 To articulate technology capabilities roadmaps and investment priorities to the broad science community**

Setting investment priorities is always a sensitive and challenging task, but it is a critical element in the planning phase. Planning within the ESTP is guided by the science objectives and priorities as shown in Figure 3. The science community, at large, is also eager to learn about the development objectives and priorities of the ESTP to help guide science investigation planning. This somewhat circular process can be positively iterated by broad outreach and clear articulation of the program priorities on both sides.

**2.3.9 To broadly disseminate technology development status and articulate the TRL level of the ESTP-funded technologies so that potential science PIs can propose to use these technologies with confidence**

This need is closely tied to the need for the ESTP to effectively infuse developed technologies into future missions to ensure that the benefits of the investments are realized, as was discussed in paragraph 2.2.4.

**Applicationists’ Needs for the ESTP:** According to the ESE Applications Strategy [25], the applications function of the ESE builds on the strengths and results of ESE science and technology programs. A primary applications goal is to translate the information and knowledge gained from science and technology R&D advances into societal benefits. ESTP’s development programs and the results of these programs are therefore of significant interest to the applications community. The needs of the applicationists for ESTP are similar to those of the scientists, i.e., they need the ESTP to articulate technology capabilities roadmaps and investment priorities, and to broadly disseminate technology development status of the ESTP-funded technologies, as were discussed in paragraphs 2.3.8 and 2.3.9, to help the community plan applications research and incorporate the technologies into operational systems.

**NASA Centers’ Needs for the ESTP:**

**2.3.10 To fund more technical development tasks at Centers in order to build core competency and to help bring future ESE missions to Centers**

First, it has to be recognized that core competency is a strategic issue that is much bigger than the ESTP. In the classic paper of Prahalad and Hamel [26], “core competence” is defined as a set of long-term capabilities that can provide the corporation competitive advantage in the marketplace, while the strategic business units of the corporation use these capabilities to enhance the current competitiveness of the firm. Developing core competencies is, therefore, an Agency strategy. It has become more of an issue in the past decade mainly due to two trends: one, downsizing of the agency and the decline of the Agency budget as discussed in section 1.1, the other, shifting of R&D resource allocation from the “Research Technology Operating Plan” (RTOP) funding that is more directed in nature to a “Broadly Announced, Peer Reviewed” (BAPR) competition like the NASA Research Announcement (NRA) and the Announcement of Opportunities (AO). NASA Centers are asked to compete, along with others, on these research and mission opportunities, and most of the competitions and funding are on a three-year cycle.

While there is merit for the peer-review selection process and for periodically renewing the competition to make sure relevant and promising technologies are being developed, the uncertainties of the competition outcome and the uncertainties of the long-term funding profile have caused serious concerns that some core competencies of NASA are at risk for being lost. For capabilities that need a longer development time, a three-year funding cycle may not provide enough stability and continuity required for an institution to commit its human capital and other resources to grow the core competency, whether it’s a NASA Center or an industrial company. NASA has, therefore, tried to identify a list of core competencies that are considered critical to the Agency’s future, and has looked into various mechanisms that could foster their development. It should be noted that these core competencies can be built in a competitive fashion and not necessarily by NASA Centers, but issues of funding continuity and stability have to be addressed.

The core competency issue of NASA is complex and deserves a separate and extensive study alone. A positive contribution toward preserving core competencies



at NASA Centers, from ESTP's perspective, is to be cognizant of the need for greater funding stability and continuity for the technologist community, as was also discussed in paragraph 2.3.6.

**Other NASA Technology Programs' Needs for the ESTP:** We focus our discussions in this section on cross-Enterprise technology programs that may offer the ESTP opportunities to build synergy and collaborations. These programs include the Technology for Human and Robotic Exploration And Development of Space (THREADS) Program, SBIR, PRT, and NIAC.

**2.3.11 To provide ESE needs, requirements, and Vision as input into the planning of these programs, and to provide support in the relevancy review and investment selection of these programs**

As discussed in section 1.2, NASA has a set of Enterprise-focused technology programs that are more aligned with the Enterprise mission needs, and a few cross-Enterprise "technology push" programs. To effectively complement each other and to build synergy, an Enterprise technology management program like the ESTP should actively participate in the planning, investment selection, and project review of these cross-Enterprise programs. Such participation by the ESTP would strengthen ties between these "technology-push" cross-Enterprise programs and mainstream Agency technology planning, and would, therefore, facilitate the Enterprises' buy-in on their technology products. Elements of the ESTP, on the other hand, can be used to leverage these cross-Enterprise programs in order to foster long-term advanced concepts and the more basic technology R&D that would benefit ESE in the long term.

**2.4 Additional Thoughts on the Needs**

While the Agency and the Enterprise strategies and needs play a key role in defining the goals and strategies of the ESTP, an in-depth understanding and consideration of other stakeholders' needs can help the ESTP be more effective and efficient.

After reviewing all these needs and expectations, it is fair to conclude that the ESTP may not and should not be responsive to these needs on an equal basis, as some needs are necessities, and some may be just desires or wishes. While ESTP should make every effort to coordinate and streamline its management functions and processes to fulfill the necessary needs, it is not practical to expect the ESTP to satisfy all the needs, not to mention the desires and wishes that just fall outside of the ESE's higher priorities. However, that is not to say that desires and wishes alike have no value for the ESTP planning. They could and should guide the ESTP in strategizing how it can expand its services meaningfully to satisfy more of the unmet needs or wants for the betterment of the Earth science community. These stakeholders' needs provide a grass root guide for building such a strategy.

An example is the shared desire of many stakeholders for more development funding support that, under current budget environment, is unlikely to happen. However, that should motivate the ESTP to conduct more detailed program planning to better understand the gap of its investment portfolio, the un-funded requirements and needs, the return on its current investment vs. the potential return on un-funded development. The impact analysis of the technology development shortfall on the ESE science and applications programs thus derived would add sound and quantifiable justifications to ESTP budget planning.

## **2.5 The Goals of the ESTP**

The goals of the ESTP can be derived from the synopsis of the upstream influences discussed so far in this chapter, and these goals should serve as the drivers for the management of the ESTP. However, at the top level, the strategic goals of the ESTP ought to be defined as part of the ESE Enterprise goals, and the ESE Strategic Plan [20] has defined the following goals for its technology programs:

### **ESE Technology Goals:**

***“Develop and adopt advanced technologies to enable mission success and serve national priorities.”***

- ***Develop advanced technologies to reduce cost and expand the capability for scientific Earth observation***

- *Develop advanced information technologies for processing, archiving, accessing, visualizing, and communicating Earth science data*
- *Partner with other agencies to develop and implement better methods for using remotely sensed observations in Earth system monitoring and prediction*

The ESE Technology Strategy further adds two more objectives:

- *To accomplish ESE space-based and land-based program elements effectively and efficiently*
- *To enable ESE's fundamental and applied research program goals as stated in the NASA Strategic Plan*

### **ESTP Management Goals:**

The above ESE technology goals can be decomposed into the following set of management goals for ESTP:

- G1. To articulate ESE science and applications needs and priorities, and to prioritize technology capability needs
- G2. To select ESTP investments based on the ESE science, applications, and technology needs and priorities
- G3. To manage the technology investment effectively, timely, and within budget
- G4. To demonstrate the investment return by facilitating infusion of ESTP-developed technologies to benefit ESE science and applications programs
- G5. To evaluate and report the ESTP status and progress timely to the ESE management and to actively solicit feedback from the science and applications programs
- G6. To leverage ESTP investments by partnering and collaborating with other technology programs within and outside of NASA
- G7. To recruit and retain the best people, and to encourage continuous personal and professional development

### **Validation of ESTP Management Goals:**

To make sure these ESTP management goals are representative of the success of the ESTP, i.e., they answer the needs and expectations of the Enterprise as well as the major

stakeholders, we use Table 1 to map these goals to the needs and expectations for ESTP discussed in Chapter 2. Each of the needs, including the Enterprise technology needs discussed in section 2.2, is ranked on a scale of 1 to 5 based on its perceived importance to the ESTP or the ability/capacity of ESTP to satisfy the needs. On this scale, 5 means it's an important need and the ESTP should be able to satisfy it, and 1 means either it is not critical or it is beyond ESTP's charters, and therefore, ESTP may not be able to do much about it. The relevancy of the seven ESTP management goals (G1 to G7) to each of the needs are then ranked on a scale of 1 to 3, where 3 means the goal is "highly relevant" to answering the need, and 1 being the "least relevant".

The "Needs Fulfillment Score" in the table indicates how well each need is satisfied by the seven goals, and is calculated on a normalized basis as follows:

$$\text{Needs Fulfillment Score} = 100 \bullet \sum_{i=1}^7 [(\text{GoalRelevance})_i] / (3 \bullet 7)$$

The "Weighted Goal Relevance Score" is a measure of how well each goal satisfies the twenty needs listed, weighted by the perceived importance of each of the needs, and is calculated as follows:

Weighted Goal Relevance Score =

$$100 \bullet \sum_{i=1}^{20} [(\text{Goal Relevance})_i \bullet (\text{Perceived Importance})_i] / \sum_{i=1}^{20} [3 \bullet (\text{Perceived Importance})_i]$$

Based on the assessment in Table 1, the "Weighted Goal Relevance Scores" are high across the seven goals, factoring in the differences in the perceived importance of the various needs. The "Weighted Goal Relevance Scores" range from a low of 78 to a high of 100 that indicate all seven goals are highly relevant to fulfilling the needs of the ESE and other major stakeholders. Of particular significance are the goals of "G7" and "G5"; i.e., to maintain a quality team, and to evaluate and report the ESTP status and progress timely; that are ranked top in their relevance to satisfying stakeholders' needs. There should be little surprise to their high scores because a good team is the base to any success, and evaluation and

reporting plays a significant role in the management and coordination of the ESTP, and to the planning, development, and infusion of the advanced technologies for the ESE.

The assessments also show rather high “needs fulfillment scores” that range from 76 to 100. Each of the needs has at least 4 goals that are “highly relevant” indicating that all the needs are satisfactorily fulfilled by these seven management goals. The technology needs of the ESE; i.e., the needs of advanced instrument technology, advanced information system technology, advanced platform technology, and advanced computing technology; are ranked very high. This indicates that the seven management goals devised in this chapter are highly relevant to the provision of these advanced technologies for the ESE, that is the basic need for the ESE to fund the ESTP. It should also be noted from the assessment that, if these seven goals are accomplished, the critical need to “provide adequate opportunities for flight validation/qualification of high priority technologies” should be fulfilled.

Out of the thirteen needs that are ranked as “5”, five of them have a “needs fulfillment score” of 100, and another three have a score of over 90. All these indicate the seven management goals are properly designed and are essential to the success of the ESTP.

	Perceived Importance (scale 1 - 5)	(G1) Articulate prioritized science, applications, and technology needs	(G2) Invest on ESE needs and priorities	(G3) Manage tech investment effectively	(G4) Facilitate infusion of ESTP-developed technologies	(G5) Evaluate and report the ESTP status and progress timely	(G6) Leverage investment by partnering and collaboration	(G7) Quality ESTP Team	Needs Fulfillment Score (normalized to 100)
(T.1) Instruments to lower the cost and enable new measurements	5	3	3	3	3	3	3	3	100
(T.2) End-to-end information system to transfer & transform large amount of data from space to users	5	3	3	3	3	3	3	3	100
(T.3) Platforms with reduced resource requirements, increased flexibility, & intelligence	5	3	3	3	3	3	3	3	100
(T.4) Computing and Modeling that enables integrated multi-disciplinary prediction	5	3	3	3	3	3	3	3	100
(2.2.1) Identify and manage advanced technology development needed for executing ESE strategies	5	3	3	3	3	3	2	3	95
(2.2.2) Base investment decision on overall Enterprise priorities, thus achieving overall cost-effectiveness	5	3	3	2	2	3	2	3	86
(2.2.3) Develop and mature technologies to adequate TRL prior to implementation	5	1	2	3	3	3	3	3	86
(2.2.4) Infuse the developed technologies	5	3	1	3	3	3	1	3	81
(2.2.5) Participate in Enterprise planning, coordination, integration, and outreach	5	3	3	3	3	3	2	3	95
(2.3.1) Articulate investment priorities clearly	5	3	3	1	2	3	3	3	86
(2.3.2) Elucidate various development vehicles to allow technology to mature to as high a TRL as should be	3	2	3	3	3	3	3	3	95
(2.3.3) Provide adequate opportunities for flight validation/qualification of high-priority technologies	5	3	3	3	3	3	3	3	100
(2.3.4) Help bridge connections with potential mission PIs	3	1	1	3	3	3	1	3	71
(2.3.5) Sponsor some fundamental technology R&D	2	3	3	1	1	2	3	3	76
(2.3.6) Commit to funding stability and continuity necessary to raise the TRL to a desired level	1	1	2	3	1	3	1	3	67
(2.3.7) Invest in some in-situ measurement and calibration/validation technologies	2	3	3	1	3	2	1	3	76
(2.3.8) articulate technology capabilities roadmaps and investment priorities to the broad science community	5	3	3	3	3	3	2	3	95
(2.3.9) Disseminate tech. development status and its TRL progress of the ESTO-funded technologies so potential PIs can propose to use	5	1	1	3	3	3	1	3	71
(2.3.10) Fund more technical works at Centers that contribute to core competency building	1	1	3	3	3	3	1	3	81
(2.3.11) Provide support and input to other tech. Programs including ESE priorities, review, & selection	3	3	3	1	1	2	3	3	76
Weighted Goal Relevance Score (normalized to 100)		86	87	88	91	97	78	100	

Table1. Mapping of ESTP Management Goals to Needs for ESTP

### **Chapter 3 The Management Functions of the ESTP**

Driven by the top-level technology goals defined by the ESE and the set of seven ESTP management goals articulated in section 2.5, this chapter devises and discusses critical management functions needed to accomplish these seven management goals, and thus the overall technology goals of the ESE.

A total of twenty-six management functions are considered essential to the accomplishment of the seven ESTP management goals, and are discussed in more details in the sections to follow. The discussions in this chapter generally follow the current organization form of the Earth Science Technology Office (ESTO), i.e., program planning functions (section 3.1), technology development management functions (section 3.2), infusion functions (section 3.3, currently part of planning at ESTO), and program administration (section 3.4). An ESTO organization chart is included in Appendix C for reference.

For a quick reference and overview, these twenty-six functions are:

**A. Program Planning Functions:**

1. CNA: Capability Needs Assessment
2. SAS: System and Architecture Studies
3. TAP: Technology Assessment and Projection
4. OP: Outreach and Partnership

**B. Technology Development Management Functions:**

5. IM1: Instrument Technology Portfolio and Investment Planning
6. IM2: Low-TRL Instrument Technology Development Selection, Implementation, and Management
7. IM3: Mid-TRL Instrument Technology Development Selection, Implementation, and Management
8. IM4: High-TRL Instrument Technology Development Selection, Implementation, and Management
9. IM5: Instrument Technology Development Status Reporting and Information Dissemination

- 10. IS1: Information System Technology Portfolio and Investment Planning
- 11. IS2: Low-TRL Information System Technology Development Selection, Implementation, and Management
- 12. IS3: Mid- TRL Information System Technology Development Selection, Implementation, and Management
- 13. IS4: High- TRL Information System Technology Development Selection, Implementation, and Management
- 14. IS5: Information System Technology Development Status Reporting and Information Dissemination
- 15. PT1: Platform Technology Portfolio and Investment Planning
- 16. CT1: Computing Technology Portfolio and Investment Planning
- 17. CT2: Low-TRL Computing Technology Development Selection, Implementation, and Management
- 18. CT3: Mid- TRL Computing Technology Development Selection, Implementation, and Management
- 19. CT4: High- TRL Computing Technology Development Selection, Implementation, and Management
- 20. CT5: Computing Technology Development Status Reporting and Information Dissemination

C. Infusion Functions:

- 21. IP: Infusion Planning
- 22. IF: Infusion Facilitation
- 23. IE: Infusion Enabling

D. Program Administration Functions:

- 24. EC: Enterprise Coordination
- 25. KM: Knowledge Management
- 26. HRM: Human Resources Management

This Chapter concludes with a check on the completeness of the suite of management functions by cross-linking these twenty-six functions against the management goals to make sure all goals are served properly.



### 3.1 Program Planning Functions

Program planning for ESTP, in a broad sense, is similar to the marketing functions in an industrial company. Marketing can be defined as: “the process of identifying customer needs and satisfying the needs by identifying new product and market opportunities, and to oversee the launch and promotion of the new product” [11, 27]. Marketing therefore serves as an important mediator between the firm and its customers.

To ensure that ESTP is aligned with the Enterprise’s priorities and provides value to the broad Earth science community, program planning needs to interface with all the major stakeholders. Program planning is a multi-faceted process that involves:

- assessing current and future science and applications needs for technologies,
- strategizing future mission architecture and implementation options,
- managing trade studies to evaluate different technology options,
- assessing current technology capabilities and projecting future technology trends,
- identifying technology capability gaps, and
- prioritizing the ESTP technology development needs.

All program planning functions should include a strong coordination element to make sure that relevant information is shared across the ESTP management, and is widely disseminated to the Earth science community.

These planning functions are discussed in more details below. The overall information flow and the coordination of the planning functions is summarized in Figure 4.

#### 3.1.1 Capability Needs Assessment (CNA)

**CNA Functional Goal:** To continuously update ESE science/applications needs, measurement requirements, implementation options, and technology capability requirements by working with lead Earth system scientists, applicationists, and technologists, and to publish the ESE-validated and HQ-approved CNA document at least bi-annually.

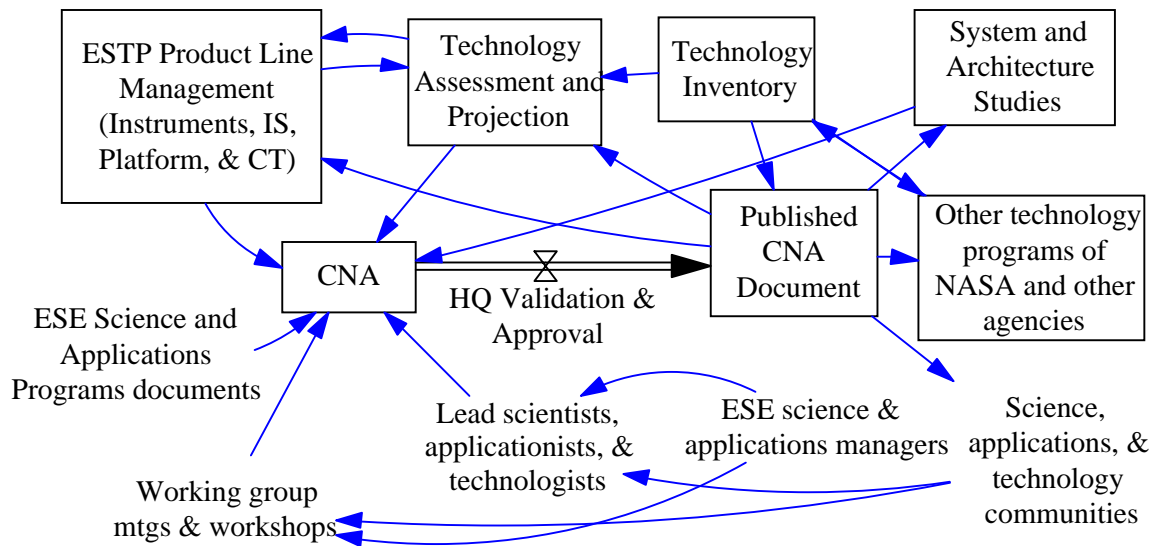


Figure 4. Information Flow and Coordination of Program Planning

The CNA captures the ESE science/applications needs and the technology capability needs at system, key subsystem, and component levels. The information gathered by the CNA and presented in the CNA document forms the basis of ESTP planning. Due to the broad coverage of science, applications, and technology, it is a challenging task to adequately gather, assess, and validate all these needs and requirements. Published documents from the ESE science and applications programs such as the ESE Research Strategy [28] and the ESE Applications Strategy [25] must be carefully digested to extract the needs and requirements. Meeting reports from ESE-sponsored science and applications working groups should be assessed and synopsized, and close involvement of lead representatives from the science, applications, and technology communities is critical to the accuracy and authenticity of the CNA. It should be cautioned that building a consensus in such a broad community is not easy and interpreting the needs and requirements by different groups may produce conflicting results. The process to conduct the CNA, therefore, should not only pay attention to the needs and requirements, but should also make sure that all disciplines and major stakeholders are adequately represented in the process and that key issues and concerns are at least being discussed. The collection and assessment of needs and requirements should be performed on a continuous basis whenever credible information becomes available. However, the final

published CNA document must be vetted by the ESE Enterprise management before publishing to ensure the accuracy of the content.

The CNA document serves as the basis for ESTP to track and control the measurement requirements and technology options, and to establish traceability of these requirements to science/applications needs. This document articulates the ESE technology development interests and priorities to the broad science/applications/ technology communities and to other technology programs within and outside of NASA for coordination and collaboration. It provides a foundation for architecture and system engineering analysis. When combined with technology development inventory, it also allows the ESTP-funded development projects to be traced to the requirements, and facilitates gap analysis and technology infusion planning.

### **3.1.2 Systems and Architecture Studies (SAS)**

**SAS Functional Goal:** To define and refine science, applications, and technology requirements and to provide the context for technology option and trade studies by identifying and managing advanced mission architecture and system studies, and to sponsor ESE Vision planning and advanced concepts studies.

The System and Architecture Studies should include the following:

- Advanced mission architecture studies: In over four decades of space-based Earth observation, observation system architectures have consistently evolved with the advancement of technologies. Constellation and fleet operations are becoming standard practice, and with a future vision of a “sensor web” concept as articulated in the ESE Strategic Plan, this trend of constellations of interacting small Earth observing satellites is likely to continue and increase in complexity. It is important that ESTP invests in advanced mission architecture studies that better define the science and technology requirements and constraints envisioned with these advanced architectures. Such studies also provide a context for conducting technology option and trades studies and help assessing the priorities of technology capability needs. Lastly, these studies may help facilitate future technology infusions and have a

chance to impact future ESE missions. A separate MIT System Design and Management (SDM) Program thesis by Gordon Johnston [29] offers more details and insight on the subject of advanced architectures of Earth observation networks.

- Technology options and trades studies: Options and trades studies ought to be conducted under high-level mission architectures/scenarios, as was discussed in the previous paragraph. The objectives of these studies are to further our understanding of technology needs, constraints, and capabilities, and to better define the scope of potential technology developments.
- ESE Vision and Advanced Concepts: For long range strategic planning purpose, ESE has been developing a future Enterprise vision of twenty years and beyond that projects a state of scientific knowledge and technology capabilities capable of producing 10-year climate forecasts, 15- to 20-month El Nino predictions, 12-month regional rain rate estimates, 60-day volcano warnings, 10-14 day weather forecasts, and etc. [20, 30]. The ESE Vision planning should lead to the identification of advanced concepts to be sponsored by ESE. Such studies should also seek synergy with other advanced concepts programs such as the THREADS and NIAC.

The content of the CNA provides a base for the selection and conduct of these System and Architecture Studies, while the results from these studies help crystallize the science and technology capability needs, requirements, and constraints thus supplementing the CNA with substantive information. The synergies among the three major activities covered by SAS, as discussed above, should also be noted.

### **3.1.3 Technology Assessment and Projection (TAP)**

**TAP Functional Goal:** To refine the technology capabilities assessment by performing feasibility studies, to project and understand future technology trends by conducting technology roadmapping, and to identify and prioritize investment opportunities by tracking technology development projects and conducting gap analysis.

The Technology Assessment and Projection activities should include the following:

- **Feasibility studies:** It is important that ESTP maintains a high-level understanding of the capabilities and constraints of the current and leading technologies, and the promise of potential new capabilities. The need for a feasibility study is high for technologies that may enable new science measurements and applications especially when the projects demand high resource commitment and may incur high development risks. Feasibility studies at an early stage can help ESTP and its stakeholders better understand the potential and constraints of these technologies, and help the developers better understand the barriers to overcome to achieve the technology goals. An example can be given using the space-based lidar for wind measurement, a feasibility study at a system level that considers the laser transmitter power and receiver aperture size, the transmitter pointing accuracy and stability, and the platform movement control can provide a good insight on the final measurement accuracy and the feasibility of such a system to meet science needs. A system engineering analysis then can help point out high priority developments needed to improve the overall system performance.
- **Inventory and gap analysis:** An inventory of technology development projects funded by ESTP and by other NASA technology programs that benefit ESE should be conducted on an annual basis. Traceability to the technology capability needs and science/applications needs should be established to help facilitate the gap analysis that identifies those under-invested capability needs and points out their priorities. This information will provide a basis for the investment planning.
- **Technology roadmapping:** In the current mode of a 3-year project funding cycle, it is important for the broad Earth science community to have a continuous and coherent technology vision that lasts beyond than 3 years. Technology roadmapping is a tool for projecting future technology capabilities advancement and trends. ESTP leadership, with inputs from the technologist community, should play a key role in providing this vision.

It should be noted that TAP activities do require significant involvement of technology development managers who manage technology projects on a daily basis and are in position

to observe trends in capability needs and technology advancements. However, due to the broad implications of the TAP activities on overall ESTP planning, these activities should be led by the program planning functions with significant inputs from the development side of the ESTP.

#### **3.1.4 Outreach and Partnership (OP)**

**OP Functional Goal:** To maximize return on ESTP technology investment by articulating the science/applications/technology capability needs of the ESE to other NASA technology programs, other Federal agencies, and industries to facilitate collaboration and partnership.

As discussed in section 1.2 and again in paragraph 2.3.11, NASA has a mixed set of Enterprise-sponsored and cross-Enterprise technology programs, and they can complement each other in a very synergistic way to help maximize the investment return for both. The synergy exists because the Enterprise-sponsored technology programs invest more on science-driven and application-oriented technologies; while the cross-Enterprise programs fund more advanced concepts that involve generic and basic technology research. The complement is rather obvious and natural. ESTP ought to collaborate more closely with these cross-Enterprise programs to promote those advanced concepts and basic technology R&D projects that have a potential to serve future ESE requirements. In return, ESTP should actively support the planning and execution of these cross-Enterprise programs, and continue funding promising projects after they graduate from these advanced concepts programs.

For external partnership, NASA's approach to investment decisions can be paraphrased as "buy when feasible, build when necessary." Driven by the space-based communications industry, worldwide commercial investment in space technologies is now reported to exceed Government investment, and viable space-based commercial remote sensing companies are emerging [29]. It is in NASA's interest to cultivate the commercial sector so this technology capability pool can continue to grow; and by building synergistic partnership with the industry, it allows ESTP resources to be focused on critical needs not available from other sources. ESTP therefore should broadly disseminate its CNA, its technology roadmaps, and

its technology inventory to the aerospace industries, and to seek partnerships that will maximize mutual leverage and benefit.

### **3.2 Technology Development Management Functions (TDM)**

Based on the ESE business processes illustrated in Figure 2, and the technology needs of the ESE discussed in section 2.2, the following four technology “product lines” are being managed by ESTP:

- A. Instrument Technology: Currently, ESTP invests in the instrument technology through the ACT and the IIP projects. ACT projects invest in technologies with lower TRL (2-5), and IIP projects fund low- to mid-TRL (3-6) technologies. The New Millennium Program (NMP) has the major responsibilities to advance technologies to high TRLs (beyond TRL 7) through flight validation/qualification, especially for technologies intended for space-borne. It is ESTP’s intention to fund the development of both passive and active remote sensing technologies employing the entire electromagnetic spectrum, the advanced “photon-less” sensors, and selected in-situ and airborne sensing instruments.
- B. Information System Technology: ESTP funds end-to-end information system technologies through the Advanced Information System Technology Projects (AIST) that include six categories: Data Collection, Transmission, Data and Information Production, Analysis, Search, and Display, Systems Management, and Infrastructure. AIST invests in information system technologies at all levels of TRL, except for those aimed for space validation and qualification that is a critical function of the NMP.
- C. Platform Technology: Platforms provide the environment, housekeeping, and communication functions for the hosted sensors. ESTP currently does not have funding allocated to invest in platform technologies, and much of the management attention on platform technologies is to pursue leveraging opportunities in existing, funded programs such as PRT, SBIR, etc. The requirements and needs for platform technology capabilities, however, include seven categories: Power, Propulsion,

Thermal, Materials and Structures, Guidance, Navigation, and Control, Communications, and Command and Data Handling.

- D. Computing Technology: ESTP funds scalable computational technologies and software tools to further the development of Earth science models, simulations, and analyses of data products, with a goal of facilitating integrated multi-disciplinary global simulations. The Computing Technology (CT) Project funds, in general, ground-based systems and therefore invests in technologies at all levels of TRL.

The goals and functions of managing these four technology lines are similar. We, therefore, define the generic goals for the technology development management functions in the following paragraphs; that should apply equally well to the four technology product lines:

**Generic Goals for Technology Development Management Functions:** To solicit and select technology development projects based on the prioritized technology capability needs and the gap analysis, to mature the selected technologies effectively and within budget by demonstrating the performance capabilities and retiring the risks to an acceptable level for infusion, and to maintain a balanced technology development portfolio across the TRL spectrum.

In general, low-TRL projects are more generic and conceptual, and the risk of application is high; the time frame for the potential adoption of such technologies is, therefore, farther away. However, the demand of resources for low-TRL development is also low. The high-TRL projects, on the contrary, have more matured performance, are closer to being adopted for specific applications and, therefore, have retired more risks. However, the resources required to continue the development are usually high due to the intensity of the development effort at this stage.

ESTP needs to ensure that its technology pipeline remains consistently productive in the future; therefore, development projects in low-, mid-, and high-TRL ranges should be properly balanced so that the far-, mid-, and short-term ESE technology needs can be



satisfied. In this thesis work, we have defined the “low-TRL” to be from 2 to 4, the “mid-TRL” is 5 or 6, and the “high-TRL” to be 7 and above. Projects with TRL of 1 are more of advanced concept studies that were discussed in paragraph 3.1.2.

Decision gates may be put in place to review the progress of the technology developments and to re-assess the relevancy of the technologies being developed. One example is the transition of technology development from the low-TRL ACT Project to the mid-TRL IIP Project; at which transition point, all projects have to be re-proposed and re-competed in order to for funding support to continue. ESTP management, however, should make sure the transition of development activities between projects is conducted smoothly and the technology PIs are well informed and guided by the ESTP’s planned investment priorities.

The technology development managers should also ensure expedient implementation of competitively selected projects and manage and report the status of these development projects timely and properly based on the ESTP-approved project plan.

We have defined the following five generic TDM functions:

- TDM1 To conduct technology inventory, and to assess and prioritize technology capability needs for investment planning. To provide input to the CNA, and to collaborate with Program Planning managers on the Technology Assessment and Projection (TAP) activities discussed in section 3.1.3.
- TDM2 To select and implement low-TRL component and subsystem technology development projects based on ESTP priorities and to manage the development according to the ESTP-approved project plan.
- TDM3 To select and implement mid-TRL component, subsystem, and system technology development projects based on ESTP priorities and to manage the development according to the ESTP-approved project plan.
- TDM4 To select, implement, and manage high-TRL technology validation/ demonstration/qualification projects based on ESTP priorities and needs.

TDM5 To report on the status and progress of the technology development projects and to disseminate, broadly and appropriately, information on technical advances to the Earth science communities

A total of 20 specific TDM functions can be enumerated by combining the five generic TDM functions and the four technology product lines. They can be grouped as shown in the following 5x4 matrix.

	Instrument	Information System	Platform	Computing
<u>TDM1</u> : Technology Portfolio and Investment Planning	<u>IM1</u>	<u>IS1</u>	<u>PT1</u>	<u>CT1</u>
<u>TDM2</u> : Select, implement, and manage low-TRL technology projects	<u>IM2</u>	<u>IS2</u>		<u>CT2</u>
<u>TDM3</u> : Select, implement, and manage mid-TRL technology projects	<u>IM3</u>	<u>IS3</u>		<u>CT3</u>
<u>TDM4</u> : Select, implement, and manage high-TRL technology projects	<u>IM4</u>	<u>IS4</u>		<u>CT4</u>
<u>TDM5</u> : Reporting and information dissemination	<u>IM5</u>	<u>IS5</u>		<u>CT5</u>

Table 2. Sixteen Technology Development Management Functions

Because the platform technology line currently does not have funding authorized, the management function for platforms is limited at this time to planning activities that include the CNA and the TAP. Therefore, a total of 16 specific TDM functions can be enumerated and their descriptions are similar along each row of Table 2. Examples can be given below for the TDM functions for managing the instrument technology product line:

- IM1: To collaborate with program planning managers in conducting inventory, and investment planning and prioritization for instrument technologies.
- IM2: To select, implement, and manage low-TRL instrument technology projects based on ESTP priorities and approved project plans
- IM3: To select, implement, and manage low-TRL instrument technology projects based on ESTP priorities and approved project plans

- IM4: To select, implement, and manage high-TRL technology validation/  
demonstration/qualification of instruments based on ESTP priorities and needs
- IM5: To report on the status of the instrument technology projects and to disseminate,  
broadly and appropriately, information on technical advances to the Earth science  
communities

The overall information flow and coordination of the technology development management functions can be summarized as shown in Figure 5.

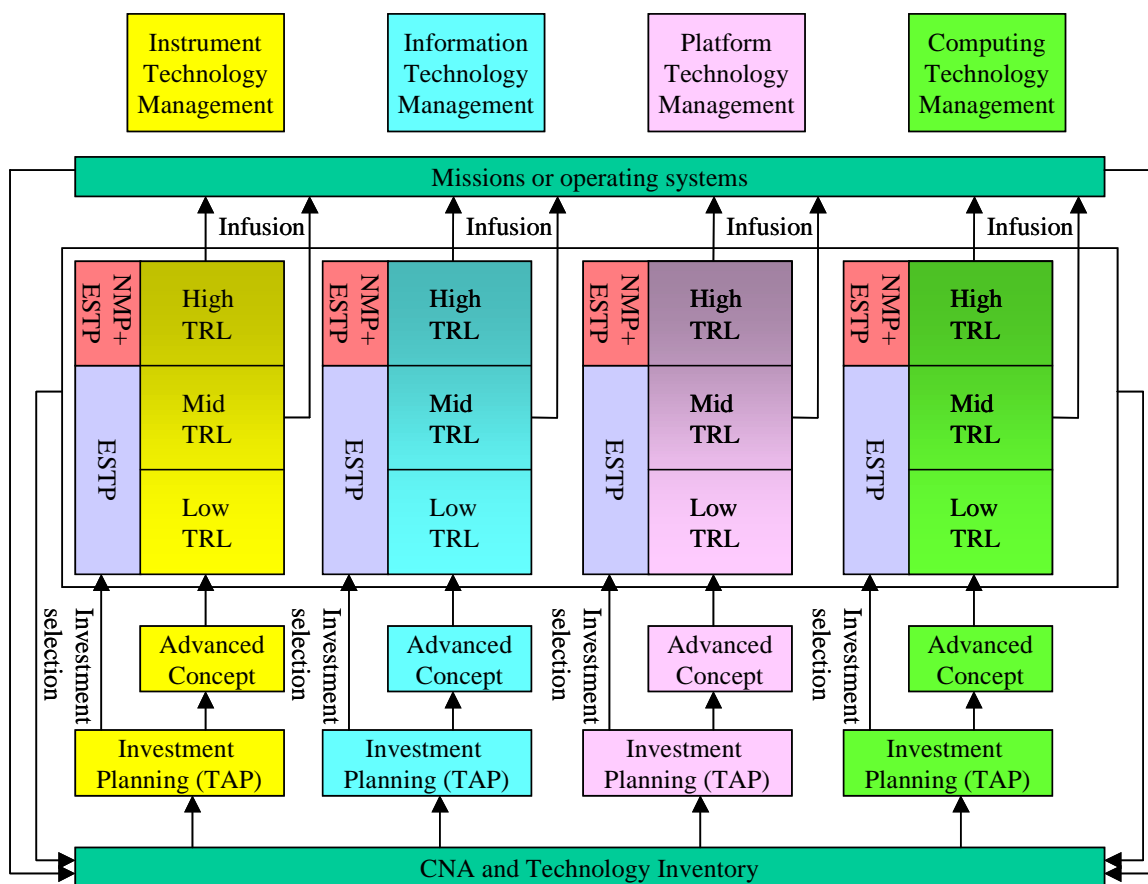


Figure 5. Information Flow Associated with Development Management

### 3.3 Technology Infusion Functions

The goals ESE set for its technology programs are to “develop and adopt advanced technologies to enable mission success and serve national priorities” [20]. It is arguable that “adoption” is the most challenging part of the goal; yet, this is where ESE benefits the most

from its technology investment, and why an Enterprise needs to fund a technology development program of its own. In the context of ESE, there are three barriers to the infusion of new and advanced technologies: organizational, cultural, and technical.

**Organizational Barrier:** As discussed in sections 2.2.2 to 2.2.4 and in the ESE Technology Infusion Plan [17], the creation of the ESTP arose from the needs of ESE to consolidate its technology investment to allow Enterprise-wide prioritization and to maximize the overall cost-effectiveness of its technology investment. However, separating the technology development from the projects also created an organizational barrier to the technology infusion. First, the “buy in” by the projects is no longer automatic because, after all, the project manager did not make the decision to invest in these technologies. Secondly, the additional organization boundary does not help communicating to the project managers or PIs the benefits these new technologies offer to entice infusion. In the PI-led missions, this barrier can be significant if the PI is not a resident of a NASA Center, thus even less familiar with the ESTP investment.

**Cultural Barrier:** The culture of flight project management is known to be “risk averse”, and for a good reason: a project manager gets rewarded for completing a project on schedule and within budget. Incorporating new technologies goes against these criteria as it introduces something that may cause performance problem at mission level, and may cause schedule delay and cost overrun if additional development is needed. Therefore, the benefit of adopting a new technology has to be direct and critical, and the risk has to be well understood and mitigated to incentivize the PIs and project managers. Basically, most people prefer to be the “second” user, and not the “first” one.

Consequently, as the technology is developed and matured from the more “generic”, low-TRL component level to the application-specific high-TRL system level, the potential PIs and project managers need to be involved or informed as much as possible, both on the advancement of the technical performance and the effort and progress on risk mitigation.

**Technical Barrier:** For space-borne technologies, the risk of adoption can become high enough that space validation/qualification is required to advance these technologies to beyond TRL 6 before the infusion can occur. The ESE has designated the responsibilities to plan and to conduct technology demonstration/ validation/qualification in a space environment to the NMP, as shown in Figure 5. However, as was discussed in section 2.3.3, although the NMP has been successful in building a “technology demonstration” mission such as the EO-1, it does not seem to have provided adequate opportunities to meet the growing needs for technology validation/qualification in space. Therefore, it is critical that ESE and ESTP enhance the infusion functions to address the unmet needs and to increase the flight validation/qualification opportunities.

To sum it up, it requires integrated and focused infusion planning and management to overcome these infusion barriers. The infusion functions needed to meet the infusion goals are infusion planning, infusion facilitation, and infusion enabling, and they will be discussed in more details in the next few paragraphs. These three infusions functions can be exercised separately as parts of the program planning and the technology development management functions discussed in sections 3.1 and 3.2, but due to the importance of infusion to the ESTP and the ESE, this study suggests that the infusion functions be grouped together to facilitate a close coordination among them and to improve the effectiveness of infusion.

### **3.3.1 Infusion Planning (IP)**

The key for infusion is to get the buy-in from the potential mission PIs. One way to get the buy-in is to involve the science community as early as possible by working jointly with lead scientists and institutions, and NASA HQ science managers to plan and articulate mid- and long-term science measurement scenarios and technology infusion opportunities.

Seeking and planning for opportunities to conduct flight validation/qualification of technologies with high potential is a critical part of infusion planning. One important venue is ESE mission formulation and development. ESTP should participate in these activities to actively explore and sponsor opportunities for hitchhike or secondary payload to conduct such flight-testing. Other space flight opportunities including free flyers, Shuttles, and even

Space Station should be pursued if feasible. Joint planning and partnering with flight-testing programs of other federal agencies, especially those of the Armed Forces and the intelligence agencies, and even industries should also be actively sought after to facilitate the risk mitigation and maturing of technologies and to enable more robust infusion. Adequate funding should be provided to incentivize and create flight validation opportunities.

This function can be part of the program planning. The joint planning with science community can be part of the Systems and Architecture Studies (SAS), and the results can be incorporated in the CNA when appropriate. The execution of this function, however, should be sensitive and careful enough so that the broad community will not interpret it as an endorsement by the Enterprise on a specific measurement.

### **3.3.2 Infusion Facilitation (IF)**

It is a common belief that: “If you build it (and build it right), people will come.” Ultimately, if the new technologies offer significant cost savings and/or performance enhancement, incorporating these advantages into mission designs should increase the chance of generating a winning proposal. However, the key is to continuously involve and inform the science/applications community on technology advances so they are aware of the advantages, and to help facilitate collaboration and partnership between scientists/applicationists and ESTP-funded technology developers so the potential PIs are comfortable proposing the new technologies.

This function can be part of the Technology Development Management (TDM) functions.

Several mechanisms can be identified to facilitate this function:

1. Distributing project management responsibilities to the ESTO Associates, i.e., staff technology managers located at participating NASA Centers (See the ESTO organization chart in Appendix C), based on the local science and technology expertise of the Center to better inform and involve the local science expertise.

2. Involving lead scientists in the mid-term or final review of ESTO-funded projects to gain credibility of the TRL assessment of the technologies, and to familiarize the science community with the technology advances.
3. Broadly disseminating the technology performance advances to the potential science PIs through conferences, symposiums, and workshops. Currently, ESTO organizes and hosts an annual Earth Science Technology Conference (ESTC) that exhibits the technical progress of ESTP-funded projects. A more preferred forum may be to hold the ESTC in conjunction with, or be a part of major Earth science and technology conferences such as the American Geophysical Union (AGU) annual meetings, or the International Geoscience and Remote Sensing Symposium (IGARSS). This will significantly broaden the audience and can help facilitate future infusion as well as potential collaboration and partnership.

### **3.3.3 Infusion Enabling (IE)**

The flight validation and qualification of new technologies is critical for the infusion decision, especially for missions that involve the acquisition of long-term data sets and missions of operation agencies. The opportunities of such flight tests are very limited; therefore, the candidates for flight validation and qualification have to be critically identified with the needs and requirements of flight-testing clearly articulated and managed. ESTP needs to actively seek opportunities to conduct testing in a space flight environment and to manage the validation/qualification effort effectively and efficiently.

The overall coordination between the infusion functions and the program planning and technology development management functions can be shown in Figure 6.

## **3.4 Other Functions**

Because technology, science, and applications constitute the three main enabling functions of ESE, there is a clear need for a central technology management service at the Enterprise level. As an Enterprise technology program, ESTP needs to perform the following functions that offer value-added services to the Enterprise:

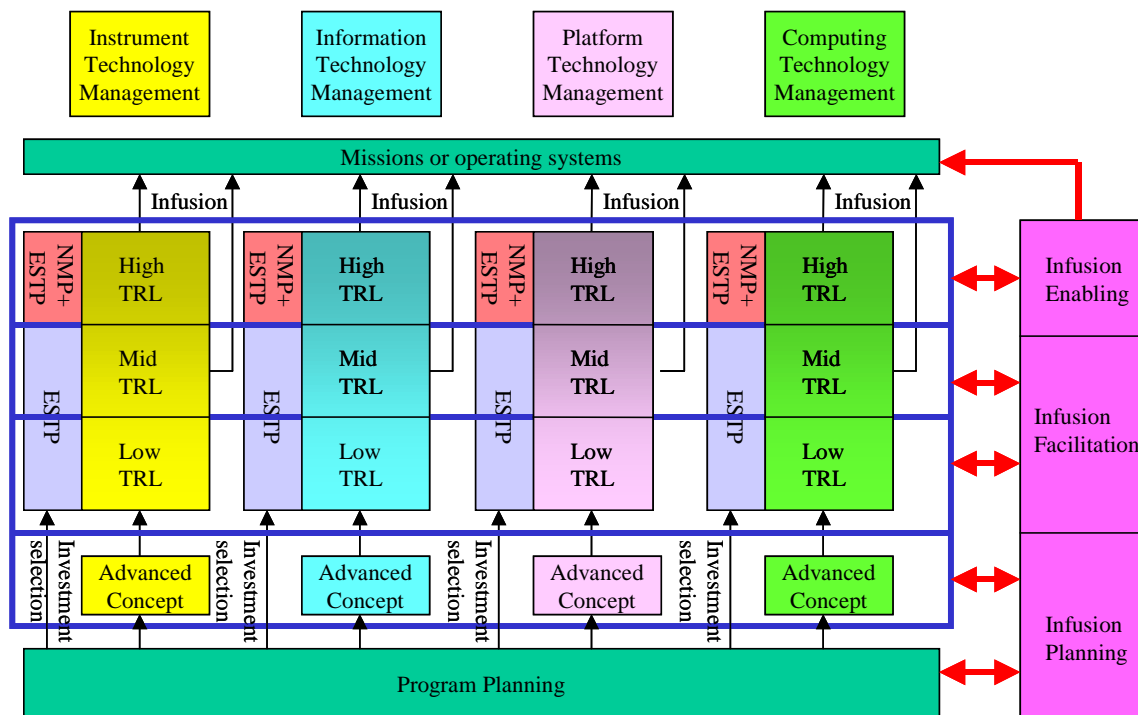


Figure 6. Coordination and Integration between Infusion and Planning and Development Management

**3.4.1 Enterprise Coordination (EC):** To make sure Enterprise needs and expectations of the ESTP are satisfied, and that the technology function is well coordinated with the science and application functions at the Enterprise level, ESTP needs to articulate the technology capabilities and development needs in the process of Enterprise strategic planning and budgeting, to evaluate the progress of its technology investment periodically, to report insightfully and timely on the aggregate status and progress of ESTP investment to the ESE senior management, and to solicit feedback. ESTP also needs to work in collaboration with the science and applications programs in formulating new Enterprise missions and projects.

**3.4.2 Knowledge Management (KM):** As the central knowledge depository of ESE-funded technology activities, ESTP needs to ensure that progress and lessons learned of ESE-funded technology development are properly collected, documented, organized, archived, and can be easily accessed by required personnel for future reference.



**3.4.3 Human Resource Management (HRM):** Last, but not the least, it is people that are behind every performance number of an Enterprise, and one can never over-emphasize the importance of personnel. It is well recognized that a competent team is responsible for most of the success that is achieved; while good management fosters and facilitates teamwork, and ensures that the team members continue stay atop in what they do. ESTP therefore needs to ensure key positions are filled with the best-qualified people, and to encourage continuing personal and professional development of the ESTP staff.

ESTP should make sure that the workload is evenly and equitably distributed among team members, and that an individual's performance plan is established according to the functional goals this individual serves. Realistic, yet challenging, performance metrics should be established jointly by the individual and the ESTP. Adequate travel and training budget should be made available for the team members based on the individual's approved travel plan and Individual Development Plan (IDP).

### **3.5 The Linkage of Management Functions to Management Goals**

In Table 3 below, the 26 ESTP management functions enumerated in this Chapter are cross-linked against the management goals discussed in section 2.5. The purpose is to make sure that these management functions do serve the goals, and that all management goals are served properly. The relevancy of these management functions against each of the seven management goals is rated by either 1 or 2, where 2 means the function "critically serves" the goal, and 1 means the function "generally serves" the goal. Each of the 26 management functions are then weighted by summing up the product of "Goal Relevance Score" and "function relevance" as shown below:

$$\text{Function Weight} = \sum_{i=1}^7 [(\text{GoalRelevance})_i \bullet (\text{FunctionRelevance})_i / 100]$$

The "Function Weight" factor provides a rough estimate of the overall contribution of each of the functions to the fulfillment of ESTP management goals in satisfying the ESE technology and strategic needs and the needs of the major stakeholders. Two functions stand out above the rest are the "Human Resources Management" function and the "Infusion

Enabling” function. A quick reference to the seven management goals indicates that these two functions are directly relevant to the two top-ranked goals; i.e., to maintain a quality team, and to evaluate and report the ESTP status and progress timely, that in turn serve the most critical needs of the ESE and other major stakeholders.

It should be cautioned that the “Function Weight” factor only serves as a qualitative guide for allocating “management attention”, and is by no means an indication of the required effort and the workload needed to perform the subject function. Therefore, the “Function Weight” factor should not be the sole basis for function allocation of staff or for team organization. Chapter 4 will take a more in-depth look at these organization and integration issues.

		(G1) Articulate prioritized science, applications, and technology needs	(G2) Invest on ESE needs and priorities	(G3) Manage tech investment effectively	(G4) Facilitate infusion of ESTP- developed technologies	(G5) Evaluate and report the ESTP status and progress timely	(G6) Leverage investment by partnering and collaboration	(G7) Quality ESTP Team	Function Weight
	Weighted Goal Relevance Score (from Table 1)	86	87	88	91	97	78	100	
Program Planning	Capability Needs Assessment (CNA)	2	2		1	1	2		6.9
	Systems and Architecture Studies (SAS)	2	1		2		1		5.2
	Technology Assessment and Projection (TAP)	2	2		1	1	2		6.9
	Outreach and Partnership (OP)	1	2	1	2		2		6.9
Development Management	Instrument investment planning/prioritization (IM1)	2	2		1	1	2		6.9
	Low-TRL Instrument Investment selection, implementation, and management (IM2)	1	1	1		2	2		6.1
	Mid-TRL Instrument Investment selection, implementation, and management (IM3)		2	2	2	2			7.3
	High-TRL Instrument validation/qualification (IM4)		2	2	2	2	2		8.8
	Reporting and disseminating instrument development information (IM5)	2		2	2	2	1		8.0
	Info. System investment planning/prioritization (IS1)	2	2		1	1	2		6.9
	Low-TRL Info. system Investment selection, implementation, and management (IS2)	1	1	1		2	2		6.1
	Mid-TRL Info system Investment selection, implementation, and management (IS3)		2	2	2	2			7.3
	High-TRL Info system validation/qualification (IS4)		2	2	2	2	2		8.8
	Reporting and disseminating Information System development information (IS5)	2		2	2	2	1		8.0
	Platform investment planning/prioritization (PT1)	2	2		2	1	2		7.8
	Comput. Tech. investment planning/prioritization (CT1)	2	2		1	1	2		6.9
	Low-TRL Comput. Tech. Investment selection, implementation, & management (CT2)	1	1	1		2	2		6.1
	Mid-TRL Comput. Tech. Investment selection, implementation, & management (CT3)		2	2	2	2			7.3
	High-TRL comp. system validation/qualification (CT4)		2	2	2	2	2		8.8
	Reporting and disseminating Computing Technology development information (CT5)	2		2	2	2	1		8.0
Infusion	Infusion Planning (IP)	2	1		2		2		6.0
	Infusion Facilitation (IF)		1	1	2	2			5.5
	Infusion Enabling (IE)	2	2	2	2	2	2		10.5
Administration	Enterprise Coordination (EC)	2	2		2	2	1		8.0
	Knowledge Management (KM)	2		2	2	2	2		8.8
	Human Resource Management (HRM)	2	2	2	2	2	2	2	12.5

Table 3. Linkage between Management Functions and Management Goals

## **Chapter 4 Functional Organization and Program Integration**

A dominant and classic management belief is that an organization can be designed and rationally optimized to maximize the efficiency and effectiveness of the organization in accomplishing its strategic goals [31]. Galbraith and Lawler [32] reflected this perspective in a statement that “ultimately, there may be no long-term sustainable advantage except the ability to organize and manage.”

In the first three chapters of this thesis, we have gone through some key steps in the strategic design of an organization by articulating the strategic and management goals of the ESTP, and by establishing key management functions that the ESTP must carry out to achieve its goals. In this chapter, we attempt to study the grouping and organization of these functions, and the required linkages and integration of these functional groups.

### **4.1 Functional Organization Analysis Using Design Structure Matrix**

Design Structure Matrix (DSM) began as a system modeling tool in the 1960s [33], and gained widespread attention and acceptance in the 1990s as a tool for system analysis and design and for project management [34, 35]. As a system analysis tool, DSM provides a compact and clear representation of a complex system and offers a visual image that captures the interactions/interdependencies/ interfaces between system elements. A concise tutorial of DSM can be found on the MIT DSM research team website [36]. However, the analysis in this chapter should be illustrative enough to the basic construct and use of DSM.

DSM is applied to study the organization of the 26 ESTP management functions discussed in Chapter 3. The analysis is based on information flow between these functions in an attempt to group them more effectively and to highlight necessary linkages across these functional groups. A DSM, shown in Table 4, lists the 26 ESTP management functions down the side of the matrix as row headings and across the top as column headings in the same order. If the performing of function  $i$  requires information from function  $j$ , then the matrix element  $ij$  (row  $i$ , column  $j$ ) is marked. Otherwise, the element is left empty. A quick example can be given by looking at the “row” of the function IM3 in Table 4. The marks in that row reveal that

performing IM3 requires information from IM1 and IM2. A similar reading of the IM3 “column” shows that IM3 feeds information to IM1, IM4, IM5, IF, EC, and KM. The diagonal elements of the matrix have no significance in describing the system and are therefore blacked out.

In Table 4, we also labeled the current ESTO organization grouping in the boxes labeled “planning,” “implementation,” and “ESTP administration.” It shows that there are a lot of important interactions outside the “Planning” and “Implementation” groupings. Some of these interactions are being addressed by ESTO through formal processes, while others are dealt with on an ad-hoc base.

	CNA'	SAS	TAP	OP	IM1	IM2	IM3	IM4	IM5	IS1	IS2	IS3	IS4	IS5	PT1	CT1	CT2	CT3	CT4	CT5	IP	IF	IE	EC	HRM	KM
CNA'		X	X	X	X					X					X	X					X		X		X	
SAS	X		X	X																	X			X	X	
TAP	X	X		X	X					X					X	X					X		X	X	X	
OP	X		X																		X			X	X	
IM1	X		X	X		X	X	X	X												X		X		X	
IM2	X				X				X													X		X	X	
IM3	X				X	X			X													X		X	X	
IM4	X				X	X	X		X														X	X	X	
IM5					X	X	X	X																	X	
IS1	X		X	X							X	X	X	X							X		X		X	
IS2	X									X				X								X		X	X	
IS3	X									X	X			X								X		X	X	
IS4	X									X	X	X		X									X	X	X	
IS5										X	X	X	X												X	
PT1	X		X	X																	X			X	X	
CT1	X		X	X													X	X	X	X	X		X		X	
CT2	X															X				X		X		X	X	
CT3	X															X	X			X			X	X	X	
CT4	X															X	X	X		X		X	X	X	X	
CT5																X	X	X	X						X	
IP	X	X	X		X					X					X	X						X	X	X	X	
IF						X	X	X				X	X	X				X	X	X	X		X		X	
IE	X		X	X				X					X						X		X	X		X	X	
EC	X	X	X	X		X	X	X	X		X	X	X	X			X	X	X	X	X		X		X	
HRM	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
KM	X	X	X	X		X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	

Planning

Implementation

ESTP Administration

Table 4. DSM View of ESTP Function Coordination

The matrix can be manipulated in order to obtain clusters of highly interacting groups while attempting to minimize inter-cluster interactions. This process is referred to as "clustering".

The obtained groupings represent a useful framework for organizational design by focusing on the predicted communication needs of different functional groups. Clustering the DSM thus provides us with insights into optimal team formations based on the degree of interactions among functions. The ESTP Function matrix in Table 4 can be “clustered” by rearranging the rows and the corresponding columns, and the resulting groupings are shown in Table 5.

	IM1	IM2	IM3	IM4	IM5	IS1	IS2	IS3	IS4	IS5	CT1	CT2	CT3	CT4	CT5	CNA'	SAS	TAP	OP	PT1	IP	IF	IE	EC	HRM	KM
IM1		X	X	X	X											X					X					
IM2	X															X		X	X			X		X		
IM3	X	X														X						X		X		
IM4	X	X	X													X						X		X		
IM5	X	X	X	X												X										
IS1							X	X	X	X						X		X	X		X					
IS2						X				X						X					X		X			
IS3						X	X			X						X					X		X			
IS4						X	X	X		X						X					X		X			
IS5						X	X	X	X							X										
CT1											X	X	X	X	X	X		X	X		X		X			
CT2											X					X					X			X		
CT3											X	X				X					X		X			
CT4											X	X	X	X	X	X							X		X	
CT5											X	X	X	X									X		X	
CNA'	X					X					X					X	X	X	X	X	X		X			
SAS																X		X						X		
TAP	X					X					X					X	X		X	X	X					
OP																X	X	X					X			
PT1																X	X	X	X	X	X		X			
IP	X					X					X					X	X	X	X	X		X	X	X		
IF			X	X	X			X	X	X			X	X	X	X					X		X			
IE				X					X					X		X		X	X		X	X		X		
EC		X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X		X		X			
HRM																										
KM		X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	

Table 5. Proposed ESTP Management Teams and Integration Processes

As suggested by Table 5, the management functions of the three “technology product lines” (excluding the non-funded platform line) are highly interacting and form natural groups. The program planning functions, including the “technology investment planning & prioritization” functions of the four product lines and the infusion planning function, are also highly interacting among themselves and can form a meaningful group. The Capability Needs Assessment (CNA) function of the program planning does feed information back to the

product line management teams, but that communication occurs in a more passive way through the CNA document, and that information can also be channeled back to the product management teams through the “technology investment planning & prioritization” function which has dual membership involving technology management and program planning groups.

Table 5 also highlights several management functions that exchange information with the majority of the ESTP program elements. These functions, such as the three infusion functions, Enterprise coordination, and knowledge management, naturally serve the program “coordination” or “integration” roles and can be performed either by establishing cross-functional teams or by formulating specific coordination processes. Some examples of the coordination/integration mechanism will be provided later in this chapter.

It should be noted that DSM analysis could be applied more elaborately in the organization design process. DSM can be a critical part of an iteration between the definition and refining of functions and the grouping and linking analysis. A DSM can also be constructed with more levels of details to better characterize the information flow so as to factor in considerations of the frequency of information exchange, the direction (one-way or two-way) and the timing (early but partial, or late but final) of communications, etc. The DSM analysis in this section is preliminary in nature, yet fruitful enough to highlight the inherent groupings and the necessary coordination processes for ESTP management organization.

#### **4.2 Vertical vs. Horizontal Integration**

The function organization analysis in section 4.1 suggests four ESTP management teams, i.e., the advanced instrument technology team, the advanced information system technology team, the computing technology team, and the program planning team, with additional functions that cut across these teams. This suggested management structure facilitates a vertical integration for the technology development management, as well as a horizontal integration that integrates ESTP products into value-added information and services to ESE. These vertical and horizontal integrations are schematically represented in Figure 7 and are discussed in the following paragraphs.

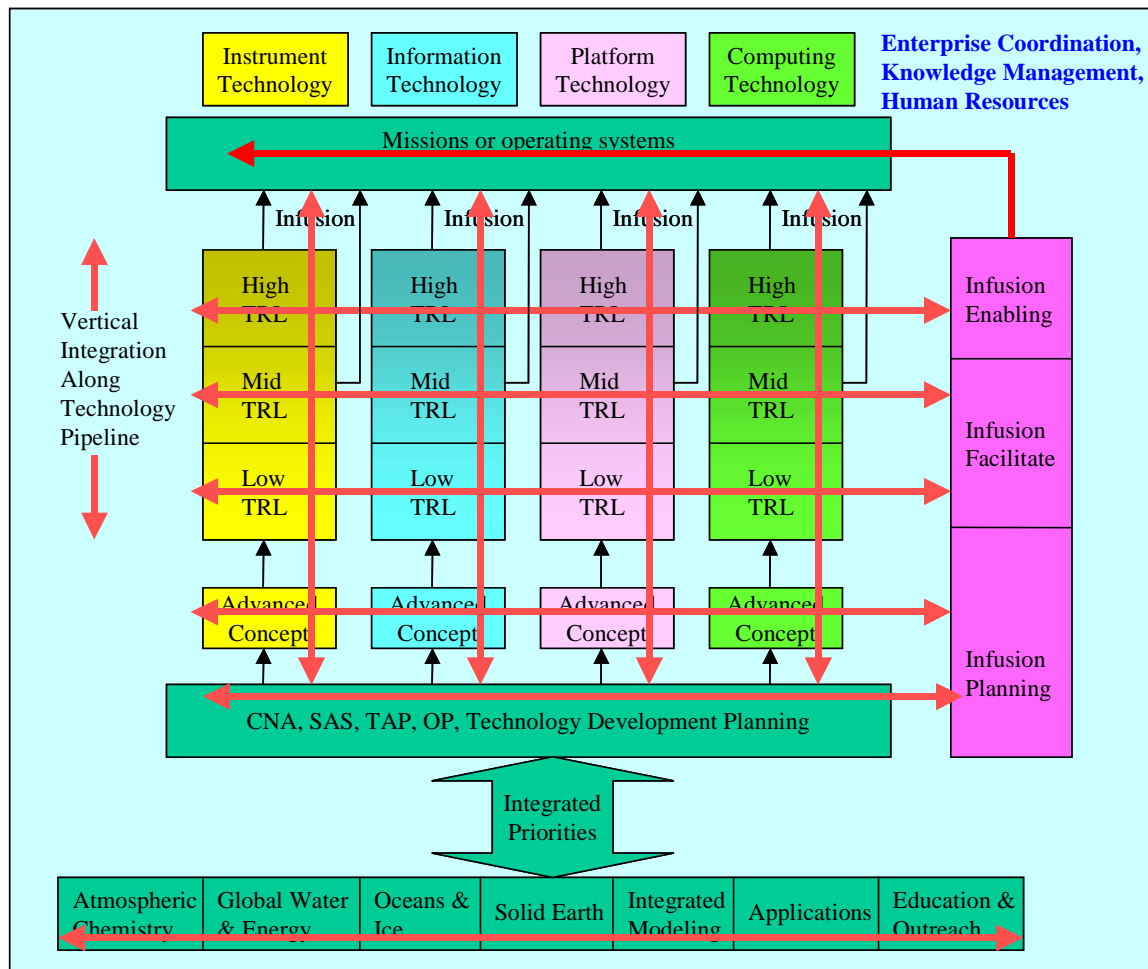


Figure 7. Vertical and Horizontal Integration of ESTP

**Vertical Integration:** The technology development managers manage the technology pipeline with goals to enable new levels of performance and capability, and to ensure new and advanced technologies will continuously be generated to meet the near-, mid-, and long-term mission needs. Management attention, therefore, should be integrated along the axis of the technology pipeline.

The integration starts with technology planning that, in the context of ESE science/ applications needs, provides critical assessment of current technology capabilities, future technology needs, and the likely trend of technology evolution. This assessment leads to an integrated investment strategy that encompasses the four technology product lines and



articulates development needs and priorities, and identifies the target time frames when advanced capabilities should be delivered.

The selection and development of technologies should be guided by this integrated investment strategy and should be managed according to the maturity of the technology and the investment level. At low-TRL, the development goal should be to expand, as much as possible, future technology solution space, and should be technology “push” in nature. The relatively low resource requirement for projects at this stage should allow a wider selection of technology concepts and components with high potential for further development. Other cross-Enterprise technology “push” programs such as the PRT, NIAC, and SBIR should be closely coordinated to maximize the leverage.

As the technologies mature into the mid TRLs, the development effort should be guided more by Enterprise priorities including plans for infusing the mature technologies. Information about the technology advances and their benefits should be actively disseminated, and collaboration with potential science/application PIs should be actively promoted.

When a technology demonstrates both a potentially high impact on science/application measurement scenarios, and a clear need for space validation or qualification, it should be considered as a candidate for flight validation and opportunities need to be created to enable the eventual infusion. Partnership with other NASA technology programs and with flight demonstration programs of other agencies ought to be pursued aggressively to make sure there is no bottleneck in the technology pipelines of ESTP.

The integration from technology planning to infusion, as discussed above, focuses on managing the technology pipeline in a way that identifies, provides, and facilitates the use of advanced technologies for the Enterprise’s near-, mid-, and long-term use. The overall integration with relevant emphases is illustrated in Figure 8.

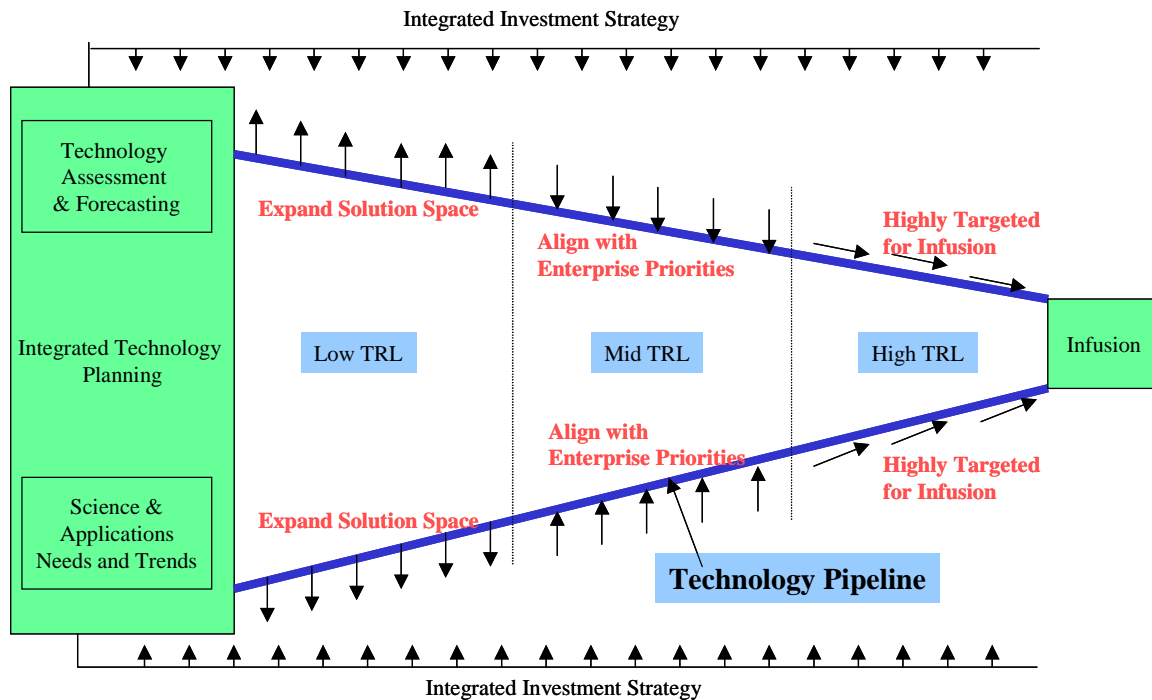


Figure 8. Vertical Integration Along the Technology Pipeline

**Horizontal Integration:** As illustrated by the business processes shown in Figure 2, ESE relies on the suite of technology developments managed by the ESTP to advance its knowledge and capabilities to understand and predict environmental changes, to deliver its products and services, and to implement its strategic goals. Therefore, there is a need for the ESTP to provide the ESE and the Earth science community an integrated service that cut-across its four technology product lines. These “cut-across”, or “horizontal” integration functions can be identified from observing the information exchange captured by a DSM shown in Table 5. It also shows horizontal integration is particularly important in three functional areas, i.e., program planning, infusion, and ESTP administration:

- a. Program Planning: As was discussed in section 3.1, program planning is similar to the marketing functions in an industrial firm that identify customer needs and satisfy the needs by identifying new product and market opportunities. Program planning, therefore, not only cuts across the four technology lines in ESTO, it also interfaces with and integrates inputs from the major stakeholders of ESTO, i.e., the Earth

science/applications communities, the ESE management, other Enterprise-sponsored and cross-Enterprise technology programs of NASA and other agencies, and industries. The program planning functions include CNA, SAS, TAP, and OP; together they formulate and form the basis for executing the ESTP.

The horizontal integration of the program planning functions, their interaction with technology development managers, and their interfacing with the Earth science community can be depicted in Figure 9.

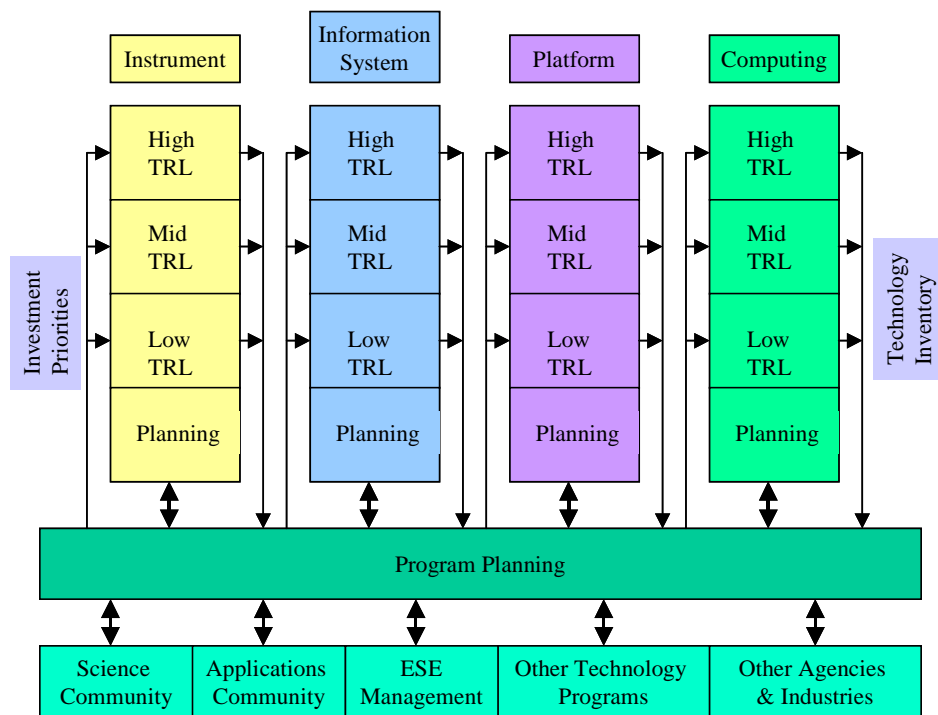


Figure 9. Integrating by Program Planning Functions

- b. Infusion: As was discussed in section 3.3, infusion can be carried out as part of the program planning and the technology development management functions. However, because of the importance of infusion to the success of ESTP, a centrally managed and integrated infusion effort may be appropriate. The integration effort of the infusion functions, their interaction with the program planning and the development

management functions, as well as their interfacing with the broad Earth science community is depicted in Figure 10.

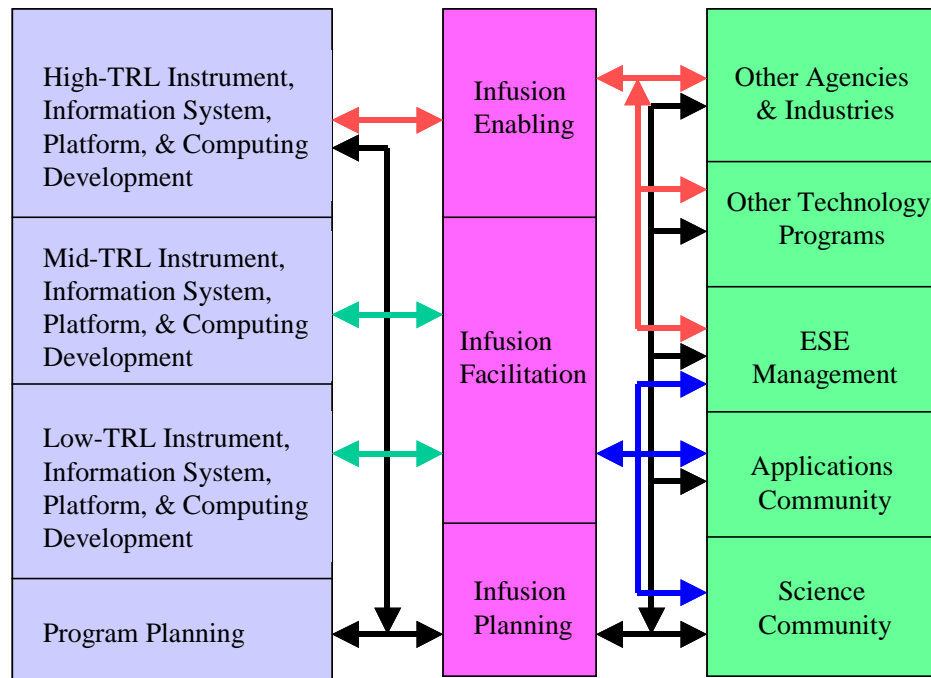


Figure 10. Integrating by Infusion Functions

- c. ESTP Administration: The administration of the overall ESTP program is critical in making sure that the ESTP is well managed, the ESTP staff are empowered and fully supported in carrying out their functions, the Enterprise' needs and expectations of ESTP are satisfied, and the technology function is well coordinated with the science and application functions at the Enterprise level. The ESTP administration therefore entails communications and coordination across the program elements and serves as the major interface with the ESE senior management.

### 4.3 Management Processes and Documents

Processes are central to the deployment of functions. In the system architecture view of Crawley [11], processes transform a set of inputs into intended outputs, and by doing so address “how” functional goals can be achieved. Process design, therefore, must be based on

well-articulated goals, and the options to deploy a specific function should be as flexible as possible in order to expand the solution space for operational concepts.

As follow-on to the functional organization analysis and the discussion of the coordination and integration of the ESTP functions in the previous two sections, this section will touch on some of the management processes needed to deploy these functions and some operation concepts that embody these processes. It is recognized that these processes are operated by the ESTO, and therefore would be best designed and refined by the ESTO. This section, therefore, only intends to provide some examples on the management processes for the “Program Planning” functions, and will not dwell on those functions of “technology development management”, “infusion”, and “ESTP administration.” The discussion in this section offers a personal view that is based very much on the current processes of the ESTO but with some modifications. The operational concepts of these processes are also discussed that include more details about what should be done and by whom; for example, the management documents that are generated or affected by these processes and how these documents in turn govern other management processes.

**Program Planning Processes:** A total of nine top-level processes to implement the program planning functions are defined and discussed in details in this section. For a quick reference and overview, these nine program-planning processes are:

1. Update Science and Applications Needs,
2. Update Implementation Options and Requirements,
3. Conduct System Architecture Studies, and Technology Options and Trade Studies,
4. Conduct Technology Feasibility Studies,
5. Conduct Technology Projection Analysis,
6. Conduct Technology Inventory,
7. Conduct Portfolio and Gap Analysis,
8. Conduct Outreach and Seek Partnership, and
9. Coordinate and Support ESE Vision Planning.

The program planning process starts with the update of the Capability Needs Assessment (CNA) document that captures and reflects ESE science/applications needs, measurement requirements, implementation options, and technology capability requirements. Due to the broad technical scope that program planning encompasses, ESTP should leverage on the expertise residing in the broad Earth science community to conduct planning activities when necessary. Ad-hoc working groups should be convened as appropriate, and the membership of these working groups should be representative of the various disciplines and should reflect a diverse and balanced set of views because of the implications of these planning activities on the execution of the ESTP.

Detailed discussions of these nine program-planning processes, together with their associated sub-processes, and the affected ESTP documents are as follows:

1. Update Science/Applications Needs: The CNA update process begins with the update of the science and applications needs and the measurement requirements that can be conducted by ad-hoc science/applications working group(s) that is (are) established jointly with NASA HQ. The sub-processes are as follows:
  - a. Establish ad-hoc science/applications working group(s) jointly with NASA HQ for the update,
  - b. Review new & updated documents generated by ESE science/ applications programs and working groups to decipher and deliberate on needs and measurement requirements, and
  - c. Organize the results and report to HQ science and applications program managers to solicit feedback.
2. Update Technology Options and Requirements: The science and applications needs and measurement requirements gathered from Step 1 are then analyzed by ad-hoc technology planning working groups to come up with implementation options and technology capability requirements in the area of instrument, platform, information system, and computing/modeling. The sub-processes are as follows:
  - a. Establish ad-hoc technology working group in each of the four ESTP-managed technology product lines for the update,

- b. Discuss implementation options and deliberate on technology capability requirements to meet the science/applications needs and the associated measurement requirements,
  - c. Identify areas that require further system and/or architecture studies to refine science, applications, and technology requirements, and
  - d. Organize the results and present to the ESE Technology Strategy Team (TST) to solicit feedback.
- 3. Conduct System and Architecture studies, and Technology Options and Trade Studies:  
 For science/applications/technology needs and requirements that demand better fidelity or sharper definition, and for technology areas that require more definitive assessment of feasibilities, high-level system or architecture studies and technology options and trades studies under these envisioned architectures should be performed. The sub-processes are as follows:
  - a. Define science/applications areas that need to be studied from a measurement system/architecture perspective, including technology options and trades, with input from Step 2c,
  - b. Decide on solicitation and funding mechanism that can be either broadly announced and competitively selected, or be directed to NASA Centers based on the level of funding and the aggregate effort,
  - c. Manage the studies to generate insightful results,
  - d. Identify technology areas that require more definitive assessment of feasibilities, and
  - e. Present the results to the TST to solicit feedback and provide the results to the CNA working groups for considerations.
- 4. Conduct Technology Feasibility Studies: For technologies that are enabling in nature or that demand high resource commitment and/or incur high development risks, an early feasibility study can help ESTP better assess the capabilities and constraints of the technologies and thus help make better-informed decisions. The sub-processes are:

- a. Identify technology areas that require more definitive assessment of feasibility, with inputs from Step 2c and Step 3d,
  - b. Direct and fund the feasibility studies at one of the leading institutions that can provide un-biased assessment, and
  - c. Present the results to the TST to solicit feedback and provide the results to the CNA working groups and to the technology projection analysis for considerations.
  
- 5. Conduct Technology Projection Analysis: Roadmaps of projected advancement in major technology areas such as the active optics or the passive microwave instruments for the next 10-15 years could serve as a valuable guide to the Earth science community. This technology projection analysis should be conducted by a workshop with leading technology experts in the field. The sub-processes are:
  - a. Organize and convene technology projection workshops for major technology categories,
  - b. Conduct technology projections with inputs from Technology Inventory and from Step 4c, and
  - c. Present the results to the TST to solicit feedback and provide the results to the technology investment planning for considerations.
  
- 6. Conduct Technology Inventory: The NASA Chief Technologist conducts annual technology inventory of all technology development projects funded by NASA that documents, among others, the objectives, technical progress and TRL, and funding level of the project. ESTO has been responsible for conducting the inventory for all ESE-funded technology development projects since its inception. The sub-processes are:
  - a. Coordinate with all ESE programs and projects that have funded technology development/validation projects to ensure the timely update of the inventory records,
  - b. Review all inventory records for completeness and accuracy and to submit the records to the ESE management for approval, and
  - c. Submit the inventory records to the Office of Chief Technologist.



7. Conduct Portfolio and Gap Analysis: ESTP planning and technology development managers should jointly conduct a portfolio and gap analysis and use the results as a basis for ESTP investment planning. The sub-processes are:
  - a. Establish traceability of ESTP-funded development projects to the technology capability needs and science/applications needs, and have a comprehensive understanding of what science needs and technology capability needs are being funded, and at what TRL is the development,
  - b. Identify and prioritize those capability needs that are under-invested, and
  - c. Present the data to the TST to solicit feedback and provide the results to the technology development managers for investment selection considerations.
8. Conduct Outreach and Seek Partnership: Outreach and partnership must be actively sought after to leverage ESTP investment and maximize the return, and to seek flight-testing opportunities through partnership with other NASA technology programs, and programs of other federal agencies, especially those of the Armed Forces and the intelligence agencies. The sub-processes are:
  - a. Identify potential partners and the goals and areas for collaboration/partnership,
  - b. Identify resource requirement of ESTP and the expected resource commitment from potential partners, and
  - c. Reach out and engage in joint planning and negotiation.
9. Coordinate and Support ESE Vision Planning: ESE has been developing a future vision of its mission of twenty years and beyond for long-range planning of the Enterprise, and ESTP has been playing a major supporting role in Vision planning. The advanced system and architecture studies and the technology projection analyses conducted by the ESTP should provide valuable input to the Vision planning.

These nine program-planning processes, their sub-processes, and the associated ESTP documents affected by these processes are summarized in Table 6 below.

Processes	Sub-processes and Operation Concepts	Function	Documents
1. Update Science & Applications Needs	(a) Establish ad-hoc science/applications working group(s) jointly with NASA HQ (b) Review new & updated documents generated by ESE science/applications programs and working groups to decipher and deliberate on needs and measurement requirements (c) Organize the results and present to HQ science/applications program managers to solicit feedback	CNA'	CNA'
2. Update Implementation Options and Requirements	(a) Establish ad-hoc technology working group(s) in each of the four ESTP-managed technology product lines (b) Discuss implementation options and deliberate on technology capability requirements to meet the science/applications needs and the associated measurement requirements (c) Identify areas that require further system and/or architecture studies to refine science, applications, and technology requirements, and identify technology areas that require more definitive assessment of feasibilities (d) Organize the results and present to the TST to solicit feedback	CNA, TAP	CNA'
3. Conduct System and Architecture studies, and Technology Options and Trades Studies	(a) Identify science/applications areas that need to be studied from a measurement system/architecture perspective, including technology options and trades, with input from step 2c (b) Decide on solicitation and funding mechanism that can be either broadly announced and competitively selected, or be directed to NASA Centers based on the level of funding and the aggregate effort (c) Manage the studies to generate insightful results (d) Identify technology areas that require more definitive assessment of feasibilities (e) Present the results to the TST to solicit feedback and provide the results to the CNA working groups for considerations	CNA, SAS, TAP	CNA'
4. Conduct Technology Feasibility Studies	(a) Identify technology areas that require more definitive assessment of feasibilities, with inputs from step 2c and step 3d (b) Direct and fund the feasibility studies at one of the leading institutions that can provide un-biased assessment (c) Present the results to the TST to solicit feedback and provide the results to the CNA working groups and to the technology projection analysis workshops for considerations	SAS, TAP	
5. Conduct Technology Projection Analysis	(a) Organize and convene technology projection workshops for major technology categories (b) Conduct technology projections with inputs from Technology Inventory and from step 4c (c) Present the results to the TST to solicit feedback and provide the results to the technology investment planning	TAP, TDM1	Technology Road-maps
6. Conduct Technology Inventory	(a) Coordinate with all ESE programs and projects that have funded technology development/validation projects to ensure the timely update of the inventory records (b) Review all inventory records for completeness and accuracy and to submit the records to the ESE management for approval (c) Submit the inventory records to the Office of Chief Technologist	TAP, TDM1	Inventory
7. Conduct Portfolio and Gap Analysis	(a) Establish traceability of ESTP-funded development projects to the technology capability needs and science/applications needs, and have a comprehensive understanding of what science needs and technology capability needs are being funded, and at what TRL is the development (b) Identify and prioritize those capability needs that are under-invested (c) Present the data to the TST to solicit feedback and provide the results to the technology development managers for investment selection considerations	TAP, TDM1	CNA, Solicitation
8. Conduct Outreach and Seek Partnership	(a) Identify potential partners and the goals and areas for collaboration/ partnership (b) Identify resource requirement of ESTP and the expected resource commitment from potential partners (c) Reach out and engage in joint planning and negotiation	OP, IE	ESTP Infusion Plan
9. Coordinate	and Support ESE Vision Planning	SAS	ESE Vision

**Table 6. Processes to Implement the ESTP Program Planning Functions**

## **Chapter 5 Summary and Conclusions**

Managing technology is a complicated and challenging undertaking. Many great technology firms failed because of wrong technology investment decisions; many suffered seriously because the key technology they developed missed the product schedule, or because they failed to develop necessary core competencies to strengthen their long-term competitive advantage; and still many others just withered slowly away because they did not have a rigorous planning process and could not manage their technology development programs efficiently or effectively.

The task of technology program management at NASA is stringent because of the cutting-edge nature of technology R&D, the strict mission requirements imposed on technology development, and the Agency's constricting budget resources for technology development. Although NASA does not exhibit monetary profit on a balance sheet, the success of its technology development is critical to the premier leadership of the United States in the worldwide space endeavor. NASA technologies have also been credited for benefiting the US economy and society by enabling new businesses and markets, providing quality jobs, and improving the quality of life beyond short-term monetary measures.

This thesis studies the strategic issues involved in the planning and integration of the NASA ESTP, a technology program that is funded and managed by the NASA ESE, and is responsible for "developing and adopting advanced technologies to enable ESE mission success and serve national priorities" [20]. A system architecture framework is closely followed in this study to devise a management system for the ESTP.

The end-to-end analysis begins with a comprehensive review of the upstream influences on the ESTP, including a review of the mission and unique capabilities of the ESE, the strategic technology needs of ESE, and the needs and expectations of the ESE and other major stakeholders for the ESTP. Seven management goals of the ESTP are then derived from the synopses of these upstream influences, and are crosschecked with the stakeholders' needs to make sure these management goals are essential to the success of the ESTP. It is found that

these goals are highly relevant to the needs of the Enterprise and other major stakeholders, and that all the identified needs are fulfilled with these seven management goals.

A total of twenty-six management functions are devised and discussed in depth, following the definition of management goals. A Design Structure Matrix (DSM) is used to study the organization of these ESTP management functions based on the information flow between them. Results of the study suggested a more effective grouping of these functions in six groups; i.e., a program planning group, three technology development management groups, a technology infusion group, and an ESTP Administration group. Necessary linkages within and across these functional groups are also devised and discussed in order to seek more effective integration, both vertically within the technology product lines and horizontally across the ESTP.

This study recognizes the central role of processes in deploying management functions. However, it also recognizes the existence of multiple options for processes, and respects the ownership of these processes by the ESTP staff. Therefore, only management processes for the program planning functions are reviewed and examined in this thesis to serve as examples. The discussions of these program-planning processes, though extensive, are based very much on the current processes associated with the ESTP though with some modifications.

It is hoped that this study will contribute to a comprehensive understanding of the critical stakeholders' needs, a more clearly defined set of management goals, a sharpening of the definition of key management functions, a more effective function allocation and organization, and a systematic program integration with better connected management processes that will enhance the planning, development, and infusion of advanced technologies. Although this study focuses on the technology program of one NASA Enterprise, it articulates issues and strategies that are common to technology programs across NASA, and therefore can be modeled and applied to other NASA technology programs.

Dwight Eisenhower once said, "planning is everything, the plan is nothing" [38]. The insight, in most cases, comes from going through the process; words on paper usually do not fully reflect the tacit knowledge gained. In the process of this thesis study, this author has learned a great

deal about the intricacies of managing technology programs at NASA, and has benefited much more than the quality of this thesis can indicate. Limited by time and personal expertise, this thesis is very preliminary indeed. However, it is hoped that the system architecture framework exemplified in this study can benefit our pursuit of management effectiveness, and provide valuable insights for the many seasoned technology managers at NASA.

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## **Appendix A: Sample questions to guide interviews with NASA Program Managers**

1. What are some of the specific needs and expectations for ESTO from the Enterprise perspectives? How is ESTO performing against these needs/expectations overall?
2. Out of the management elements of planning, investing (selection), maturing, and infusing, which one is the weakest link in the ESTP management and why? Are there other critical elements ESTP is blindsided?
3. In your opinion, what purposes does an ESE Capability Needs Assessment document serve? How well does ESTP conduct its planning activities overall? What planning activities/processes do you think are critical and would recommend to ESTP?
4. What do you think of broad competition vs. direct funding when it comes to technology investment? What is your view of the “NASA Technology Core Competency” issues? Does the Enterprise need to worry about building/keeping core competency with the compete-all-every-3-year funding mechanism? What can realistically be done to take care of the long-term competency needs of the Agency?
5. Do you think the NRA selections from IIP and AIST are adequate in answering ESE’s technology needs? Do you have any concerns about ESTP’s investment decisions?
6. How well does NASA in general balance between “mission-pull” vs. “technology-push” technology investments? What role should ESTP play in push technologies vs. making sure the Enterprise’s needs are and will be met?
7. How well does NASA in general manage the technology maturation process, i.e., from low TRL advanced concepts to a level ready to be adopted for use? Has ESTP put in adequate thoughts on the technology maturation process?
8. Has NMP met the flight validation/demonstration needs of the ES community? Is mission building the right answer for fulfilling this need? What is the role of NMP in the current Enterprise planning? Does the synergism of NMP’s portfolio of EO and ST missions really benefit ESE?
9. How can we better facilitate the integration/coordination between the two programs so they serve the ESE as an integrated program?
10. Currently, ESTP looks for cross-agency technology programs such as the NASA Institute of Advanced Concepts (NIAC), the SBIR, and the Pioneering Revolution Technology (PRT, the old cross-Enterprise) programs to provide advanced concepts and low-TRL technologies to complement ESTP’s own advanced concept studies. Has ESTP and ESE paid enough attention to advanced concepts and mission architecture studies?
11. What is your overall perception of the cross-Enterprise program now called the PRT? What are their challenges and management issues?
12. ESTO has taken more of a “marketing” approach to help facilitate infusion. Examples are the Annual Earth Science Technology Conference and the annual progress report on its investment. There are arguments that more proactive or even aggressive approaches should be taken such as, as an example, giving bonus points in AOs to people who propose to use ESTP-developed technologies; yet there are concerns about this approach. What is your opinion on this, and what advice can you give ESTP?
13. Is a web-based information system that captures and conveys the science needs, technology capabilities needs, implementation options, investment portfolio, and ES measurement scenarios worth the effort and resources to develop? What functions and features of such a system would benefit you the most?



14. What has ESTP done well so far? What overall concerns do you have with the ESTP?  
(Planning, investment selection, development management, infusion, communicating, or else.)
15. What other issues or concerns do you have about ESE's technology programs?

## **Appendix B. Definition of Technology Readiness Levels (TRL)**

<b>TRL 1</b>	<b>Basic principles observed and reported</b>
<b>TRL 2</b>	<b>Technology concept and/or application formulated</b>
<b>TRL 3</b>	<b>Analytical and experimental critical function and/or characteristic proof-of-concept</b>
<b>TRL 4</b>	<b>Component and/or breadboard validation in laboratory environment</b>
<b>TRL 5</b>	<b>Component and/or breadboard validation in relevant environment</b>
<b>TRL 6</b>	<b>System/subsystem model or prototype demonstration in a relevant environment (ground or space)</b>
<b>TRL 7</b>	<b>System prototype demonstration in a space environment</b>
<b>TRL 8</b>	<b>Actual system completed and "flight qualified" through test and demonstration (ground or space)</b>
<b>TRL 9</b>	<b>Actual system "flight proven" through successful mission operations</b>

## Appendix C. ESTO Organization Chart

